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THE LOGARITHMIC WEDGE SECTOR AND ITS USE IN QUANTITATIVE SPECTRUM ANALYSIS

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ABSTRACT. A logarithmic wedge sector is described and its method of use and a number of factors which need attention in this connection are considered. A discussion of the validity of the law of reciprocity in the case of intermittent exposures is given. The application of the apparatus to quantitative spectrum analysis is indicated.

1. *Introduction*

THE Logarithmic Wedge Sector to be described has been designed primarily for carrying out, with modifications, the method of quantitative spectrum analysis described by Scheibe and Neuhäusser (1)*. Although it differs from the sector used by those authors in dimensions only, the method of use preferred by us is different.

The sector is used to produce by spectrography, from standard samples of metals, alloys, or solutions, of known composition, graphs which can be referred to for the analysis of other samples of unknown composition.

2. *Description of the Logarithmic Wedge Sector*

The sector is a metal disc, the outer edge being so shaped that (referring to Fig. 1), if θ represents the circumferential aperture, expressed as a fraction of a complete circle, at a distance l measured in millimetres radially inwards from the outermost part of the curve, then

(i) $$\log \theta = 0{\cdot}3 + 0{\cdot}2\, l.$$

The greatest value of l is 13·5, so that $\log \theta$ varies from 0·3 to 3·0.

The disc is made with an accuracy such that $\log \theta$ is within 0·5 per cent. of its nominal value for all values less than 2·5.

* See also reference (17).

This disc, carefully centred, is mounted on the shaft of a powerful clockwork motor, which will rotate the sector at 300 revolutions per minute for several minutes.

In use the disc is placed close in front of the spectrograph slit (see Fig. 2), and the latter uniformly illuminated. On rotation of the disc each point of the slit receives radiation intermittently, the exposure varying from point to point along the slit. If the light source is such as to give a line spectrum each line of its spectrogram taken with this arrangement decreases in intensity from one end, fading away to an extremity which can be located by any one observer with a precision of about 1/10 mm.

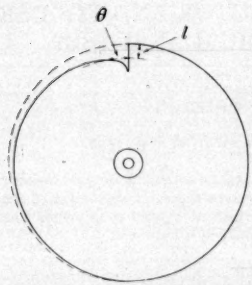

Fig. 1. Logarithmic Wedge Sector.

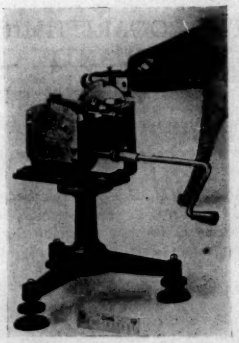

Fig. 2.

3. *Relation between the Length of a Line and its Intensity*

If a spectrum line has on two different occasions intensities I_1, and I_2, we shall see later [(4) p. 177] that the corresponding lengths of the line on the "wedge" spectrum resulting from the above use of the sector are governed by the expression

$$\log \frac{I_2}{I_1} = 0{\cdot}2\, pl, \tag{ii}$$

where l is the difference between points of the lines which in the two cases have equal blackening, and p is the Schwarzschild constant.

But one of the ways in which the wedge method of spectrophotometry is used (and this is the way selected by Scheibe and Neuhäusser and by the present authors) is to take the lengths of the spectrum lines up to the point where the blackening disappears as a measure of the intensity. The validity of the reciprocity law under these circumstances (density = 0) has been investigated by the present authors, the method adopted and results obtained being discussed in detail below. (See section 8, Calibration of the Wedge Sector.)

4. *Wedge Photometry*

Photometry by means of wedges of neutral tint glass or graduated platinum film was originated by Mees (2) and developed by Merton and Nicholson (3); and has been described at length by Dobson, Griffith and Harrison (4). With such wedges the time of exposure is the same for every point of the slit, but the intensity of light varies logarithmically from point to point. This method, and that of the logarithmic wedge sector, would be identical if the law of reciprocity held good for the end-point of the wedge sector lines, i.e. if the threshold of photographic blackening were determined by the product of intensity and time of exposure. This is known not to hold for continuous exposures*, and many measurements have been made of the well-known Schwarzschild constant†. For intermittent exposures, however, the balance of evidence is in favour of the reciprocity law holding within the accuracy which may properly be expected from the method providing the frequency of intermission, the ratio of exposure time to pause, and the degree of blackening of the photographic plate, are within certain limits.

This conclusion is not confirmed by the measurements on one kind of photographic plate which are described in section 8. Since the Wedge Sector is a convenient means of rapidly obtaining data on this subject it is proposed to continue the investigation with different kinds of photographic plates, and for all densities down to the vanishing end of the line.

As regards the carrying out of quantitative spectrum analysis by the method of wedge spectra, however, the value of the Schwarzschild constant is immaterial, provided the same procedure be adopted and the same photographic plates be used, in obtaining all the wedge spectra, see section 5.

5. *Use of the Logarithmic Wedge Sector in Spectrum Analysis*

If, with such an arrangement, spark spectrograms, for example, are taken of a series of alloys containing various known amounts of two constituents, the variation with varying composition of the relative lengths of a selected pair of lines (one due to each constituent) may be recorded and used as a means of analysing a similar alloy in which the proportion of the two constituents is unknown.

The argument may be thus stated:

The intensity I_A of a selected line of a constituent A present in a given proportion, m, will, under constant electrical and other conditions bear a constant ratio to the intensity I_B of a selected, neighbouring, line of the constituent B present in proportion n. As stated on p. 170, if l_A and l_B represent the lengths of the selected spectrum lines the ratio of the intensities I_A and I_B is given by

$$\text{(iii)} \qquad \log \frac{I_A}{I_B} = 0{\cdot}2p\,(l_B - l_A).$$

* At least where the amount of blackening is considerable, although data concerning threshold blackening were not available.

† See pp. 174–5.

For other proportions m' and n' of constituents A and B respectively, the ratio of the intensities will be given by

(iv) $$\log \frac{I_{A'}}{I_{B'}} = 0{\cdot}2p\,(l_{B'} - l_{A'});$$

hence (iii) and (iv) $$\log \frac{I_A/I_B}{I_{A'}/I_{B'}} = 0{\cdot}2p\,\{(l_B - l_A) - (l_{B'} - l_{A'})\},$$

or, in words, the change, on passing from proportion m to proportion n, in the *difference* between the lengths of the selected lines is proportional to the logarithm of the ratio of the intensities of those lines relative to each other in the two cases.

WHENEVER, THEN, THE INTENSITY OF A SPECTRUM LINE OF ONE CONSTITUENT OF SUCH AN ALLOY RELATIVE TO THAT OF A SECOND CONSTITUENT INCREASES WITH THE PERCENTAGE OF THE FIRST CONSTITUENT RELATIVE TO THE SECOND*, THE LOGARITHMIC WEDGE SECTOR AFFORDS A MEANS OF QUANTITATIVE ANALYSIS; THE DIFFERENCES BETWEEN THE LENGTHS OF SELECTED LINES OF THE TWO CONSTITUENTS OBTAINED UNDER STATED ELECTRICAL AND OTHER CONDITIONS HAVING ONCE BEEN PLOTTED AGAINST THE PERCENTAGE OF THE ONE RELATIVE TO THE OTHER IN A SERIES OF ALLOYS OF KNOWN COMPOSITION.

Fig. 3 shows the variation in length of line with varying content in the case of chromium in steel.

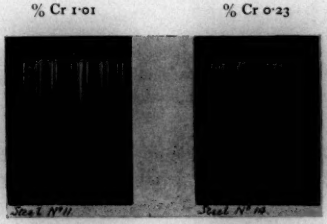

Fig. 3.

6. *Remarks on Scheibe and Neuhäusser Method*

Comparison of the statement made in section 5 regarding the relation between the intensities and the lengths of two lines, with that of Scheibe and Neuhäusser, who state that the ratio of the intensities equals the ratio of the lengths of the lines, reveals a fundamental difference in principle. Reference to the work of Holst and Hamburger (5), who developed the method for intensity measurements of multiplets from which Scheibe and Neuhäusser derive their procedure throws some light on

* Till recently we should not have thought to insert this proviso. Barratt has now shown that there are instances where an increase of percentage of a constituent does not, for a certain range of percentages, increase the intensity of its lines.

this discrepancy. Holst and Hamburger describe two sector discs, in one of which the opening is proportional to the radius, while in the other (as in the form described in section 2) the logarithm of the opening is proportional to the radius. The former was rejected on account of the variations being too small to read, but nevertheless it corresponds with the routine adopted by Scheibe and Neuhäusser although they described their sector as a logarithmic one. They say (*loc. cit.*):

> Als einfaches Mittel zur Photometrierung verwenden wir einen Sektor, dessen Ausschnitt in einer logarithmischen Funktion zunahm und der unmittelbar vor dem Spalt des Spektrographen angebracht war. Zur Intensitätsmessung von Multiplettslinien wurde diese Methode schon von Hamburger und Holst verwendet. Da die Schwärzungskurve der photographischen Platte ebenfalls nahezu logarithmisch ist, so wird die Länge der Linien auf der photographischen Platte ebenfalls etwa proportional ihrer Intensität sein.
>
> [We used a sector the section of which increased in a logarithmic function, and which was fixed directly in front of the slit of the Spectrograph. This method has already been used by Hamburger and Holst for the measurement of intensity of Multiplets. As the curve of blackening of the photographic plate is nearly logarithmic, so will the length of the lines on the photographic plate be likewise nearly proportional to their intensity. (Translation.)]

Actually the lengths of the lines on the photographic plate are *not* proportional to their intensity in the case of a logarithmic sector such as described by Holst and Hamburger. As is well known to those familiar with the method of wedge spectra, the law followed is that the *difference* in the length of lines on the photographic plate of the same wave-lengths but of varying intensity is proportional to the logarithm of their intensities. It is, we think, this misconception which forced Scheibe and Neuhäusser to lay such stress on the control of the electrical conditions of the spark, since their assumption is only true when the lengths of the lines whose intensities are compared approach equality.

This too, we think, is why they have to keep their exposures within narrow limits to avoid grave error. In fact, their application of the method amounts to little more than using it as a means of detecting small departures from the equality of the two lines which are compared.

Taking the figures which they publish, we find that for a variation of percentage of lead in tin from 3 per cent. down to 0·1 per cent., they are led to suppose that the ratio of the intensities varies only from 1·23 to 2·71. Consistency between the ratios of the intensities is obtained by omitting as "exposed too long" those readings which are not concordant with the remainder. If, however, they had, even utilising their own figures, attempted to derive intensities in the correct way, namely, from the difference in the length of the lines, it would not have been necessary to exclude these readings. These remarks must not be read as depreciating the importance of their applying, as they were the first to do, the method of wedge spectra to quantitative spectrum analysis.

7. *Intermittency and the Law of Reciprocity*

Before dealing with the care to be taken in using the wedge sector for quantitative spectrum analysis we shall consider in this and the following sections questions which would arise were it applied to photometry.

Much has been written concerning the influence of intermittency on photographic exposure, including unqualified denunciation (6) of methods of photometry which involve intermittent exposures. The balance of opinion seems, however, actually favourable to the use of intermittent exposures, and a short résumé of results may be of interest in this connection.

The objections to methods of constant exposure are grave. These objections arise from the necessity of using "neutral" tint wedges. Were there such a thing as a homogeneous non-diffusing material, from which wedges could be made, which should have a uniform extinction coefficient for all wave-lengths, these objections would disappear, or would at least be involved only in the capacity of the maker of the "wedge" to secure conformity to the assumed geometrical condition that the thickness should be proportional to the length of the wedge.

But no substance exists which even approximately satisfies the condition throughout the range of spectrum which must be used for general spectrum analysis. Such important substances as arsenic, silicon, and carbon, require for their detection—when present in percentages which are of industrial importance—wave-lengths of 2780, 2882, and 2479 A. respectively.

It is true that Merton (7) has produced wedges of platinum on quartz, but their accurate reproduction does not yet seem to be a manufacturing possibility.

It would be fortunate, therefore, if investigation were to show that the intermittent exposures (such as those employed in the sector method) are not inconsistent with an accurate knowledge of the equivalent density.

In the paper in which Schwarzschild (8) formulated the law of blackening in which his constant p appears, he points out that Schellen found the law of reciprocity to be exactly fulfilled for the same make of plate for which Schwarzschild found the value $p = 0{\cdot}86$. Numerous values of the constant have since been determined, one worker having found values ranging from $\pm$ 0·86 to 6·3.

Schwarzschild (8) also investigated the effect of intermittent exposure, using a single rotating sector. He concluded that the effect of intermittency depends upon the ratio of pause to the duration of a single exposure and on the quantity of light reaching the plate from a single exposure. The degree of blackening and the absolute magnitude of intensity or exposure had no appreciable influence. No quantitative formula was developed to express the effect.

In an investigation into the use of a rotating sector for photographic photometry, Weber (9) used several makes of plates and various sector speeds. He concludes that increase in the rate of intermission above 120 per min. is without effect upon the exposure law.

Similar results were obtained by Eckert and Pummerer (10), and much more recently by Baker (11).

A number of investigations with regard to the Hilger Sector Photometer* bear on the same point.

In a paper dealing with an investigation of the Hilger Sector Photometer method, Howe (12) wrote: "The author has found that the photographic plate, the use of which in photometric measurements is usually considered questionable, integrates intermittent exposures in such a way that the comparison of two intensities can be made directly in terms of sector openings provided that the time from the beginning to the end of the exposures is the same and that the two exposures produce equal blackening of the plate." About the same time, Martin (13) "found that perfect agreement existed between the results when transmission was assumed proportional to the ratio of sector openings, as is stated by Professor Howe."

The validity of taking the sector opening as a direct measure of intensity was subsequently considered by a group of workers at the Bureau of Standards (14) in the course of an investigation of a number of substances in the ultra-violet, visible, and infra-red regions. Visual and photo-electric null methods were also used by these workers who state "that no discrepancies have ever been noted which are larger than the experimental errors possible in the methods."

Still more recently Baly, Morton and Riding (15) have carefully compared the results given by both the Hilger sector and the Judd Lewis photometers with von Halban's photo-electric values. They find good agreement between 4360A. and 3300A., and are led to believe that the divergencies for shorter wave-lengths are due to a wave-length error in von Halban's method. This has been subsequently traced by von Halban himself to low transparency of the glass window of the cell. A comparison of the two photometers, in which, among other variables, speeds from 30 to 300 r.p.m. were used, "seem definitely to establish the fact that the Schwarzschild exponent is unity with the sector photometer and thus confirms the conclusions of the American observers."

On the above evidence, the statement of the last-named authors seems fully justified that "the sector photometer and the Judd Lewis sector spectrophotometer are both reliable instruments, and they give concordant results within a range of experimental error rarely if ever exceeding $\pm$ 2 per cent.," and that within the limits of accuracy to be expected for photographic photometry with rotating sectors, viz. about 2 per cent., the law of reciprocity holds good, i.e. that intensities can be compared when the conditions are such that the product of intensity and time of exposure is constant, when distinct blackening of the plate is in question.

8. *Calibration of the Wedge Sector*

Even with intermittent exposures, however, it is necessary to distinguish two cases, those falling in the "normal" part of the exposure curve and those falling in the region of under-exposure. The exposures with the sector photometer, if it be rightly used, correspond to the first case and the remarks cited above apply. But

* First described in the Hilger catalogue about 1913.

they do not apply when faint exposures are in question, e.g. when it is sought to determine the "end" of a line photographed through a wedge or logarithmic wedge sector. Such "ends" necessarily are under-exposed, and in these conditions Schwarzschild's constant p may, it is stated, have values less than 0·86, possibly as low as 0·6. Experiments were, therefore, undertaken with the view of obtaining data for all densities down to the lowest. They consisted essentially in using a light source whose intensity could be varied in a known way, and in making such records with the sector as could be photometrically investigated.

The source chosen was a 6-volt lamp run from accumulators whose voltage was constantly checked, and the variation of intensity was made by varying its distance from the sector. The inverse square can be relied on for calculating the intensity for so small a source. The sector was used in conjunction with a quartz spectrograph of the E 3 type, before the photographic plate of which a 1/16 inch wide diaphragm being inserted at the position of maximum sensitivity of the plate used—this position having been found from a previous experiment.

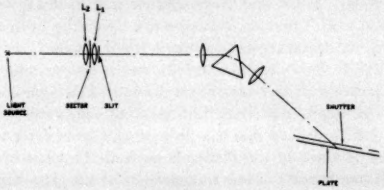

Fig. 4.

The arrangement of apparatus is shown in Fig. 4. The lamp is placed at the focus of a lens L_2, a series of such lenses being used in order to obtain a range of distances of the source. Parallel light after passing the sector is focussed by a lens L_1, placed in contact with the spectrograph slit, on to the collimator lens.

The plates used were Ilford Rapid Process Panchromatic. Three exposures were made on each plate, and the third exposure was repeated as the first exposure on each successive plate. The time of exposure in all cases was 40 seconds, the exposure being carefully timed by a Smith chronometer, the error in timing being less than 1/10 second.

The development of the plates was carried out in a special tank at the National Institute for Medical Research. The plates were placed in the tank in complete darkness, the tank closed and then flushed with clean water. This was done to ensure that when the developer was let in it would flow evenly over the whole surface of the plate. The water was let out of the tank and the developer poured in. The developer was Rodinal made to 1/20 full strength, and the time of development 7 minutes (timed by a dark room watch) at an average temperature of 18° C.

Each photograph obtained in this way consists of a uniformly exposed portion through that part of the slit which is above the sector disc, and a portion of varying density. There is a sharp dividing line between the two portions corresponding to

the circular arc of the sector (see Fig. 1). The length of each line given by the 1/16 inch wide diaphragm from the above division to a point of some agreed density was measured on the photo-electric photometer at the National Institute for Medical Research, through the kindness of Dr R. B. Bourdillon and with the assistance of Mr R. G. C. Jenkins. If the lengths of the lines be plotted as ordinates against the logarithm of the distance of light source as abscissae, a straight line results for each set of observations.

If t_1 and t_2 be the times of exposures corresponding to angular openings of the sector θ_1 and θ_2, then from the law of the sector,

$$\log t_1 - \log t_2 = 0{\cdot}2l \qquad \text{.....(1)}$$

(θ corresponds to the rim of the sector, i.e. $-\log \theta_1 = 0{\cdot}3$, and l is the radial distance in millimetres from θ_1 to θ_2).

Now Schwarzschild's law can be expressed as

$$\left(\frac{t_1}{t_2}\right)^p = \frac{I_2}{I_1} \qquad \text{.....(2)},$$

I_1 and I_2 being the intensities which, in times t_1 and t_2 respectively, will produce equal blackening of the plate,

i.e. $$p(\log t_1 - \log t_2) = \log I_2 - \log I_1 \qquad \text{.....(3)},$$

and from (1) $$\log I_2 - \log I_1 = 0{\cdot}2\,pl \qquad \text{.....(4)}.$$

But, from the inverse square law,

$$I = k/d^2, \text{ where } k \text{ is a constant;}$$

whence we obtain a relation $$2\log d = 0{\cdot}2\,pl + C,$$

factors independent of d and l being expressed by C.

The slope of the line obtained by plotting corresponding values of $\log d$ and l is, therefore, $10/p$.

Results

The first set of plates gave the following results:

Density	Schwarzschild constant, p
0·077	0·80
0·154	0·82
0·308	0·80
0·462	0·79
0·616	0·78
0·77	0·76
Mean	0·79

In the second series of exposures an attempt was made to test the uniformity of development of the plates. In this second series, in addition to photographs being taken as described above, indirect light from a 4-volt lamp passed through a tube

having a circular aperture of 5 mm. diameter at its end. This end was placed against the plate and an exposure was made near the line to be measured.

It was thought that, since the exposure of this spot would be uniform, the resulting measurement of its density should be the same in all parts of the plate if the development was uniform. However, it was not found possible to obtain any results because the patch was not uniform in itself. Its density was greatest at its centre and edges, and no reliable measurement could be made. The results for this set of plates are as follows:

Density	Schwarzschild constant, p
0·077	0·88
0·154	0·84
0·308	0·83
0·462	0·81
0·616	0·82
0·77	0·81
Mean	0·83

It will be noted that these results do not confirm the conclusions arrived at in section 7. It should be repeated that the actual value of the Schwarzschild constant, which may be expected to depend upon the particular make of plate used and the routine of development adopted, does not in any way affect the use of the logarithmic wedge sector for quantitative spectrum analysis. It does, however, have a bearing upon its use for general photometric work, and it was with this end in view that the above experiments were undertaken. Further, it is hoped to pursue these experiments when a new form of photo-electric photometer now under consideration becomes available, and to extend them into the regions of greater density.

9. *Precautions in Use*

In using the wedge sector for measurements of the intensity of spectrum lines it is necessary to secure that the variations of blackening of the photographic plate along the lines of the spectrum are entirely due to the sector. Other factors may produce such variations if not guarded against, and these must be avoided.

(1) The jaws of the slit must be parallel. This becomes of importance where a less slit width is used than corresponds with the diffraction image of the line. Since, under favourable conditions, an accuracy of intensity measurement of 2 per cent. can be reached by the wedge method, it will be seen that the accuracy of slit width desirable is very great, if the finest slit is to be used. Where the spectrum is not too complex, wide slits may with advantage be used (see section 10). Such wider slits reduce also errors arising from causes mentioned in (2) and (3).

(2) For a like reason the slit must be clean (see *instructions for cleaning slits*, issued with all Hilger spectroscopes).

(3) The definition of each spectrum line must be uniform along its length, or if this condition is not fulfilled, only so much of the length must, for best results, be utilised as is uniform.

(4) Variable magnification ("distortion") along the spectral images of the slit is a conceivable source of error, but can be ignored in all ordinary spectrographic apparatus.

(5) The sector should be placed as near the slit as possible.

(6) The spectrum lines must each be illuminated by a like area of the light source. This condition can be fulfilled by an image of the light source being formed by a spherical condensing lens not, as is customary, upon the slit, but upon the prism of the spectrograph. The position and size of the light source and the focal length and position of the condenser must be such that the image of the light source must lie wholly within the effective aperture of the spectrograph—usually limited by the prism. This is another reason why a wide slit should be used where possible —otherwise, owing to diffraction, the condition referred to in this paragraph may be difficult to fulfil.

The attainment of this condition is best assured by observation from the camera end of the spectrograph. The eye placed in the region of the visible spectrum can see the image of the light source, and the observer can thus assure himself that the image is not obstructed. A margin must be left sufficient to ensure that the condition is fulfilled not only for the visible, but for the ultra-violet part of the spectrum, and also to provide for possible wandering of the light source.

Other points requiring note are:

(7) Owing to the chromatic variations of focal length of the lenses of quartz spectrographs, the spectrum lines are of varying length, and never of the same length as the slit except at one point of the spectrum. The lengths of the "wedge" lines measured on the spectrum must therefore be corrected before any precise inference can be drawn from them concerning the variation of intensity indicated by variations in length. If observations on the standard alloys are made on the same instrument, this condition can obviously be ignored.

(8) The spectrograph must be "stigmatic," that is, a point of the slit must be represented on the photographic plate by a point image. Thus a grating spectrograph is not usually suitable unless it be of the stigmatic type.

(9) The speed of the sector must be such that during the shortest exposures the sector must make at least 40 or 50 revolutions. The spring motors provided with these sectors give 300 revolutions per minute, so that unless exposures are less than about 5 secs. this condition is observed. The reason for this condition is that part of the line receives light for a number of intermittent exposures which may be materially (a large fraction of unity) different from that operative for another part of the line.

(10) The development of the plate must be uniform. When in applying this sector to quantitative spectrum analysis by the method of Scheibe and Neuhäusser lines near to each other can be compared, little care is needed to secure sufficiently uniform development, for modern commercial plates can be relied on to be sufficiently uniform over a sufficient area for no errors to arise from this cause.

(11) It is desirable that the plates and mode of development used for the

standard range of alloys of known composition should be the same as that used in actual determinations.

(12) The substance under examination must be of uniform composition (as are most metallic alloys, solutions, and possibly powders thoroughly ground, mixed and carefully sampled).

10. *Connection between Slit Width and Intensity*

The use of the logarithmic wedge sector raises once more a point which is of great importance in spectroscopy, viz. the choice of slit width. There are two conflicting desiderata, resolution of near lines and intensity of each line, between which a compromise must be made, and it is interesting to see how far this is effected in a particular case.

The focal aperture which for a number of reasons is frequently chosen for the Hilger spectrometers and spectrographs is of the order $f/10$. The "normal slit" according to Schuster (16) for such an instrument is $10\lambda = 0{\cdot}005$ mm. for the green of the visible spectrum. A slit width of 0·02 mm., therefore, corresponds to a "slit factor" of 4, and from Schuster's table we find that the intensity is 3·15 times that for a "normal slit" or 77·4 per cent. that of an infinitely wide slit. It would appear, therefore, that for an instrument of this aperture ratio a slit width of 0·02 mm. is about as good a compromise as could be made for ordinary spectrography. Such a width is also quite suitable for the rotating wedge sector.

11. *Examination of Spectrograms*

The important point in examining the spectrograms obtained by a wedge method, including the logarithmic sector, is to determine the exact point at which a line terminates. A technique for this has already been thoroughly worked out by Merton, and it is not necessary here to more than mention his method, full details of which will be found in the references cited. The method consists essentially in forming a positive from the spectrogram and projecting this positive through a fine process screen. The resulting image is formed of a number of dots, the last of which, corresponding to the end-point of the line, can be readily observed. We find, however, that good practical accuracy can be obtained direct from the negative, using an eye-piece with 1/10 mm. scale in the focus.

12. *Application of the Logarithmic Wedge Sector to Quantitive Spectrum Analysis*

As stated at the beginning of this paper, the first object to which the sector is to be applied is that of quantitative spectrum analysis. In the paper already referred to, Scheibe and Neuhäusser give details of their investigation of (*a*) lead in tin, and (*b*) silicon and manganese in iron. In the paper by Twyman and Fitch (17) the method described in this present paper is applied to the determination in steels

of silicon, chromium, nickel, copper, molybdenum and vanadium. These suffice to show the power of the method, but naturally very much remains to be done, and it is hoped that the present paper will be the first of a series of papers dealing with these applications.

We should like in conclusion to state that the experiments described in section 8 were carried out by Mr E. S. Dreblow of the technical staff of Adam Hilger, Ltd., and to express our indebtedness to Dr Bourdillon for placing his densitometer at our disposal and for helpful discussion, and to Mr Jenkins for invaluable assistance in using the densitometer.

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DISCUSSION

Dr Judd Lewis: The communication is one of great interest and value, and the sector appears to meet satisfactorily the requirements for quantitative spectrum analysis from the optical side, which is certainly all that an instrument can be expected to do. The great hindrances to attaining the quantitative quest are the difficulties of controlling the electrical and chemical conditions under which the elements sought are excited to incandescence.

Mr Fitch: We have been investigating several applications of the wedge sector method for quantitative spectrum analysis at the Royal School of Mines, and we find that the standardisation curves for metals in solution are quite different from

those for the same metals in the solid form, as in steels. The routine adopted for steels follows closely that of Scheibe and Neuhäusser, but when subjecting solutions to the spark, special difficulties are met with, which are being overcome by means of specially devised sparking cells.

In addition to its application to the analysis of steels, the method is being used for the estimation of minor constituents affecting the market price of lead and tin concentrates and barytes, the minerals being first brought into solution. Solutions arising in leaching processes for copper and zinc ores have also been dealt with.

Mr Hitchen: I do not think that I can add very much to what Mr Fitch has already said. I would like, however, to emphasise his point regarding the spectrographic estimation of metals in solution. We have been working on this problem for some little time and sufficient has been done to show that the difficulties encountered are quite distinct from those which occur when metals are sparked in the solid state. Older forms of sparking apparatus have not proved very successful owing to incrustation of the electrodes and to the decomposition of the solution around them. We have therefore had to devise new methods of subjecting the liquid to sparking, the essential feature of which consists of continually "feeding" the electrodes with fresh supplies of the solution. The problem is not, however, entirely solved by this alone, because further investigation has shown that the spark is very sensitive to irregularities in the rate of flow (or "feed") and it is therefore necessary to keep this as constant as possible; furthermore it is desirable that it should be accomplished without the use of any complicated apparatus.

During the past few weeks I have devised and employed a new form of apparatus which appears to have overcome certain of the difficulties already mentioned and which gives good uniformity among the spectra photographed, but further tests are necessary before any claims can be made for its use.

Dr C. V. Drysdale: I feel that our President, in contributing the paper we have just heard, not only deserves our heartiest thanks for its interest and importance, but has added greatly to the prestige of the Optical Society. To those who are engaged in the analysis of complex alloys and other substances containing small proportions of several constituents I should imagine that a device of this kind would be an immense boon, and one can only admire the way in which photographic methods with their apparently unpromising and complicated manifestations have been made to yield simple and fairly accurate quantitative results.

As the object of the rotating "sector" is simply to vary the illumination along the slit according to the required law, the thought came into my mind as to whether it might not be possible to attain the same result by suitably propelling the edges of the slit. This would obviously involve extremely careful workmanship, but Messrs Hilgers have accustomed us to such a high standard in this respect as to feel that this might not be beyond their powers. Diffraction effects would probably have to be taken into account in obtaining the correct graduation of the slit, but it would certainly enhance the convenience of the instrument if the rotating sector could be dispensed with, and it would obviate the necessity for long exposures.

It also occurs to me that it might perhaps be possible by the addition of an auxiliary thin prism to project two spectra so as to overlap but with a very small horizontal displacement between corresponding lines, in which case their relative lengths could perhaps be measured usually with fair accuracy, or a single photograph would serve, and would help to eliminate errors due to exposure and development.

Mr Twyman (communicated): The question of controlling the electrical and chemical conditions mentioned by Dr Judd Lewis is one which shows the need of collaboration between workers in allied branches of science. The sparking of solutions is a branch of spectroscopy which received considerable attention at the hands of Hartley and of Pollok and Leonard, but which has since remained in practically the state left by these workers. It is, therefore, very gratifying to know that Messrs Fitch and Hitchen have been giving this attention, and that we may look forward to hearing details of the arrangements which they have made for overcoming difficulties due to incrustation of the electrodes and decomposition of the surrounding solution.

The proposals of Dr Drysdale for overcoming the use of a rotating sector are very ingenious. Our study of the literature, however, leads us to the belief that intermittent exposures are much more greatly feared than is necessary. On the other hand, such exposures have received a considerable amount of attention and we cannot help wondering if the abandonment of sector arrangement, to give place to some such arrangement as outlined by Dr Drysdale, would not lead to further considerable work of investigation of errors not inherent in sector methods.

THE LUSTRE OF TEXTILE FIBRES AND A METHOD OF MEASUREMENT

By M. O. PELTON, B.Sc.
(British Cotton Industry Research Association.)

MS. received, 6th January 1930. *Read and discussed, 10th April*, 1930.

ABSTRACT. The lustre of textile fibres is due to a geometrical property of transparent cylindrical filaments with polished surfaces. Some of the factors, notably double refraction and diffraction, which might affect lustre are discussed, and a method is suggested for measuring lustre based on the high lights visible on a curved lustrous surface.

Introduction

A LUSTROUS surface is one which, when illuminated by a unidirectional beam of light, concentrates the reflected light more in certain directions than in others. Such a surface varies in brightness according to the direction in which it is viewed, while a perfectly matt surface would under the same conditions appear equally bright from all positions.

The appearance of any cloth ready for sale is one of its most important properties, and the lustre or gloss of the surface of the fabric is one of the factors which affect its characteristic appearance.

The lustre required is, of course, dependent on the use for which the cloth is made and the tastes of the customer for whom it is intended; these again are subject to the dictates of fashion, and so are liable to change from time to time.

The various textile fibres (cotton, wool, flax, rayon or artificial silk, etc.) have different natural lustres, and this lustre can be modified to a large extent by different "finishing" treatments. Thus a fabric woven from untreated cotton is, in general, nearly matt in appearance, but the lustre can be largely increased by the process of mercerisation, which consists in swelling the cotton hairs with alkalis.

Rayon is characterised by having a very high lustre which can be largely controlled by the processes of manufacture, and its chief use is in the production of ornamental fabrics, by itself or in combination with other textile fibres.

Since the whole of a large length of cloth necessarily undergoes an identical finishing treatment after it is woven, in order that the whole length may be "level" and free from faults, it is necessary that the yarn from which it is woven shall have the same lustre throughout. Hence it is seen that the causes which affect the lustre of both the yarn and fabric must be clearly understood, and some reliable method of measurement of both these is essential.

The present paper is an account of some of the optical properties of rayon

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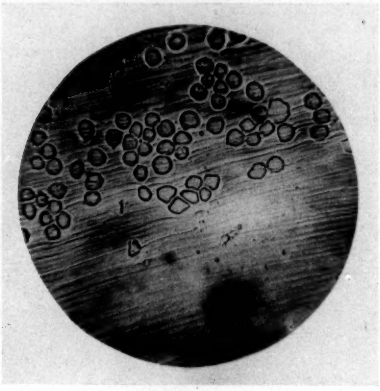

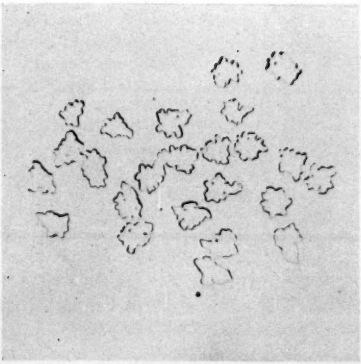

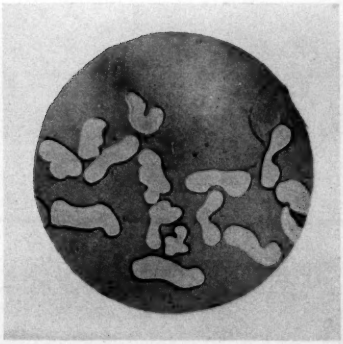

Photomicrographs of typical cross-sections of rayon. ×260

which affect its lustre, and a suggested method for measuring this. The work is, of course, equally applicable to other textile fibres.

The experimental details are discussed in the last section of this paper, but it may be briefly stated here that the distribution of the light reflected from a lustrous surface is investigated by a special form of photometer. The surface may consist of a pad of filaments held parallel to one another, yarn wound on a glass plate, or a piece of fabric held free from creases, according as the lustre of individual filaments, yarns or fabrics is being studied. The intensity of a narrow cone of light reflected from a small area, about 1 cm. square, of such a surface is measured by the photometer.

The Cause of Lustre

Rayon yarn consists of a number of continuous filaments of cellulose or cellulose acetate which are kept together by a small twist in the yarn, usually about two or three turns per inch. The individual filaments are approximately cylindrical in form, but their cross-sectional shape is very different in the different varieties (see Plate I). They are quite transparent and their surfaces are more or less polished. The filament diameters vary from about 38μ to 12μ in the different varieties, and the number of filaments making up the yarn goes from about 13 to 150. When the filament diameter is small, the number of filaments in the yarn is large and *vice versa*.

The appearance of lustre is due to the concentration in certain directions of the reflected light from a unidirectional incident beam, and to investigate this the process of reflection from a pad of parallel ideal filaments has been studied theoretically.

Theory

For the purposes of calculation, the ideal filament is assumed to have the following properties:

(1) It is cylindrical in form but not necessarily circular in cross-section.

(2) The surfaces of the filament are perfectly polished.

(3) The material of which the filament is composed is a perfectly transparent homogeneous and isotropic medium.

Consider first a ray of light reflected from such a cylindrical surface. It is a deduction from the law of reflection that the angle between the reflected ray and any line tangential to the reflecting surface at the point of incidence is equal to that between the incident ray and the same line. This means that, when a parallel pencil is reflected from a cylindrical surface, each reflected ray makes an equal angle with the generators of the cylinder, and if we consider that the diameter of the cylinder is small and that the incident beam is a narrow one, then the light reflected from the cylinder is confined to the surface of the cone, the axis of which coincides with the filament axis. The semi-angle of this cone is the same as the angle between the incident ray and the filament axis. As it will be necessary to

refer several times to this cone, it can be denoted without confusion by the term "reflection cone."

The exact distribution of light over the surface of the reflection cone will depend on the cross-sectional shape of the filament and its orientation with respect to the incident light.

Next consider a ray of light refracted through a transparent cylinder. It is a deduction from the law of refraction that the ratio of the cosine of the angle between the incident ray, and any line tangential to the refracting surface at the point of incidence to the cosine of the angle between the refracted ray and the same line, is equal to the ratio of the refractive indices of the two media.

It follows that, when a narrow parallel pencil is refracted by a small cylindrical filament, all rays on emergence lie on the surface of a cone, the axis of which coincides with the filament axis. The semi-angle of the cone is the same as the angle between the incident ray and the filament axis.

We can call this cone the "transmission cone," and it is seen that the reflection cone and transmission cone coincide.

Joint Effect of Adjacent Filaments in a Pad of Parallel Filaments

When a narrow beam of light is reflected from the surface of a small pad of filaments containing a large number arranged parallel to one another, part will have been reflected from the outer filaments only, part will have been transmitted by the outer filaments and reflected from the inner filaments, while the majority will have undergone multiple reflections and transmissions between several filaments.

Since the reflection and transmission cones for all these filaments coincide, then after any number of reflections and transmissions the light is still confined to the surface of the same cone. Also since the cross-sections of the different filaments are oriented in different directions at random, and the filaments arranged at random relative to one another, then light reflected from a number of filaments might be expected to be evenly distributed over the surface of the reflection cone.

It follows, then, that such a pad of parallel fibres will appear bright if the eye of the observer is situated anywhere on the reflection cone, but will be quite dark when the eye is off this cone.

Thus a pad of such filaments would appear highly lustrous when viewed along the length of the filaments, but it would have practically no lustre when viewed in the direction at right angles, as in this latter case the eye is always on the reflection cone, which has opened out to a single plane.

Factors which cause Modification of Lustre

In practice, as might be expected, the light reflected from a rayon yarn is not all concentrated on one cone, but there is a strong maximum in this position, and the brightness falls off rapidly as the eye moves away from a position on the reflection cone. The extent to which the reflected light is spread on either side of the reflection cone causes the characteristic lustre of that particular variety of yarn.

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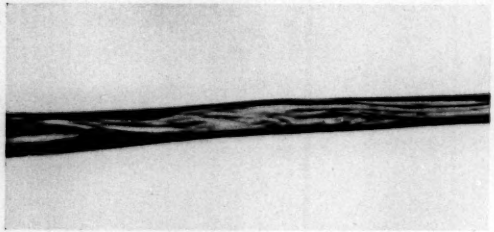
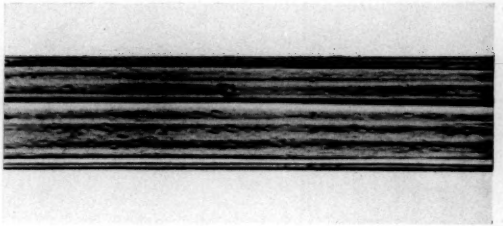
PLATE II



Filament showing departure from cylindrical form. × 270

PLATE III

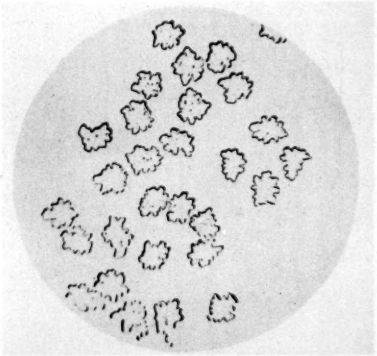


Filament showing small pits on its surface. × 525

PLATE IV

Filament between crossed nicols. Bands are strongly coloured to the eye. × 320

PLATE V



Cross-section showing oil particles within filaments. × 260

To account for this spread we must examine:

A. The degree to which the assumptions made for the ideal filament in this theory are complied with by the actual filaments produced commercially.

B. Whether the laws of geometrical optics are applicable to such small filaments, and how diffraction affects the results.

A. Dealing with the three assumptions for the ideal filament in turn, examination under the microscope shows that commercial filaments are not strictly cylindrical throughout their length. They are, as far as can be seen by eye, cylindrical over small lengths but, usually, twisted portions occur at irregular intervals. (See Plate II.)

The surfaces of the filaments are not perfectly polished. Little cracks occur every now and then, and what look like small bubbles sometimes appear on the surface. (See Plate III.) In this connection it might be mentioned that one method for "delustring" a yarn to almost any extent desired is to treat it with solutions of barium chloride and sodium sulphate in turn, so that small particles of insoluble barium sulphate are precipitated on the surface of the filaments.

Between crossed nicols under the microscope, the filaments show coloured bands running parallel to their length, and the colours are most pronounced when the filament axis is set at 45° to the plane of polarisation. (See Plate IV.) Sections of filaments do not seem to show any regular double refraction effects. These appearances show that light polarised parallel to the length of the filament has a different refractive index from that polarised perpendicular to its length, and as an approximation it has been assumed that the wave surface inside the material of the filament consists of a sphere and an ellipsoid which have a common axis parallel to the filament axis. The effect of double refraction of this type has been examined, and the mathematics are given below. The result is briefly that the concentration of light on the surface of the reflection cone is undisturbed by this type of double refraction.

The transparency of the material of the filaments is not markedly different in the different varieties. Certain rayon yarns are delustred in the process of manufacture by causing the filaments to contain small drops of oil or sulphur particles. These can be seen in the cut sections and cause a scattering of the light passing through the filament, and hence they diminish the lustre. (See Plate V.)

It must be mentioned in this connection that the appearance of a yarn is due to the joint effect of a large number of filaments. Although there may be an appreciable difference between two yarns, the actual difference in any property of the average single filament of the two yarns is probably exceedingly small, and so it is unlikely that small differences in lustre could be detected by the examination of individual filaments under the microscope.

Effect of double refraction. Let us take the axis of an ideal filament parallel to the X coordinate axis, as in Fig. 1, and let ON be the normal at a point O on the filament surface taken as origin.

Let the angle between ON and the Y axis be β. Since the filament is a true cylinder, ON always lies in the plane YOZ.

Let PO be a ray incident at O and making an angle θ with the X axis.

The coordinate axes are so chosen that PO lies in the plane YOX.

The direction cosines of the normal ON are O, $\cos\beta$, $\sin\beta$, those of the incident ray PO are $\cos\theta$, $-\sin\theta$, O. The equation to the plane wave front of which the ray PO is one normal is

$$\cos\theta.x - \sin\theta.y = Vt,$$

where V is the velocity of the wave in air, and t is the time after the wave front has passed through the origin.

Equation to the tangent plane at the point O on the filament surface is

$$\cos\beta.y + \sin\beta.z = 0.$$

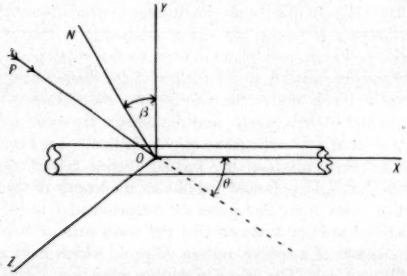


Fig. 1.

Line of contact between incident wave front and tangent plane at a time t after the wave front has passed the point O is given by the symmetrical equations

$$(x - Vt/\cos\theta)\cot\theta = y = -\tan\beta.z \qquad \text{.....(A).}$$

If μ_0 and μ_e are the two principal refractive indices of the double refracting filament, then the two sheets of the wave surface at a time t, after a disturbance at O, are

$$x^2 + y^2 + z^2 = (Vt/\mu_0)^2,$$

and

$$x^2 + (y^2 + z^2)(\mu_e/\mu_0)^2 = (Vt/\mu_0)^2.$$

The spherical sheet of this wave surface obeys the ordinary law of refraction, and has been already considered.

The wave front formed by the ellipsoidal sheet of the wave surface is given by the tangent plane to this wave surface passing through the line of intersection of the incident wave front and the tangent plane to the refracting surface.

The equation to the tangent plane to the wave surface at the point a, b, c is

$$ax + (\mu_e/\mu_0)^2(by + cz) = (Vt/\mu_0)^2,$$

and the conditions that this plane contains the line of intersection given by equation A are:

$$(1)\quad a\tan\theta + (\mu_e/\mu_0)^2(b - c\cot\beta) = 0;$$

$$(2)\quad aVt/\cos\theta = (Vt/\mu_0)^2;$$

$$(3)\quad a^2 + (\mu_e/\mu_0)^2(b^2 + c^2) = (Vt/\mu_0)^2.$$

We can solve for a, b and c from these equations, and hence obtain the wave front within the material of the filament.

Equation (2) gives $a = Vt\cos\theta/\mu_0^2$.

Now consider the point at which the ray emerges from the second filament surface, and let the direction cosines of the normal at this point be O, $\cos\beta'$, $\sin\beta'$.

On transferring the origin to the point of emergence, the equation to the wave front is

$$ax + (\mu_e/\mu_0)^2(by + cz) = (Vt/\mu_0)^2,$$

where t is the time after the wave front has passed through the origin.

The equation to the tangent plane at the point of emergence is

$$\cos\beta' . y + \sin\beta' . z = 0,$$

and the line of intersection between this plane and the wave front is given by the symmetrical equation

$$\left\{x - \frac{(Vt/\mu_0)^2}{a}\right\} \Big/ (\mu_e/\mu_0)^2(b\tan\beta' - c) = -y/a\tan\beta' = z/a \quad \text{.....(B).}$$

Now the equation to wave surface in air around point of emergence as centre of disturbance is

$$x^2 + y^2 + z^2 = V^2t^2,$$

and the tangent plane to this sphere at point a', b', c' is

$$a'x + b'y + c'z = V^2t^2.$$

One of the conditions that this plane shall contain the line of intersection (B) gives

$$a'\frac{(Vt/\mu_0)^2}{a} = V^2t^2.$$

Therefore $a' = a\mu_0^2 = Vt\cos\theta$ on substituting for a. The x direction cosine of the emergent ray is

$$a'/\sqrt{(a')^2 + (b')^2 + (c')^2} = Vt\cos\theta/Vt = \cos\theta,$$

so that also in the case of a medium with the particular double refracting properties assumed, the x direction cosine is unaltered by transmission through the filament, and the transmitted light is as before concentrated on the surface of a cone.

B. The theory which has been given takes no account of filament diameter. If the laws of geometrical optics are valid for cylinders of this degree of fineness, a similar geometrical relationship holds for all filaments and, on this basis, there seems no reason why lustre should be affected by filament size.

There is, however, a strong correlation between filament diameter and lustre, the fine filament rayon yarns being generally less lustrous than the coarser ones, and so some possible cause must be looked for.

When a fine filament is set in the path of, and perpendicular to, a parallel beam of light, diffraction causes the light to spread in a plane perpendicular to the filament axis. The distribution of the diffracted light is the same as that for a narrow slit of the same width as the filament diameter. The usual theory shows there is a maximum in the direction of the original beam and secondary maxima on either side. The intermediate minima of zero intensity are located in directions making angles of $\pm\frac{\lambda}{a}$, $\pm\frac{2\lambda}{a}$, etc., with the direction of the original beam, where d is the filament diameter and λ the wave-length of the light used. Successive maxima have intensities respectively $\frac{1}{21}$, $\frac{1}{61}$ and $\frac{1}{120}$ of that of the central maximum (see Fig. 2).

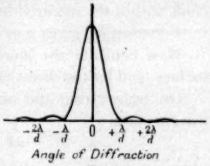
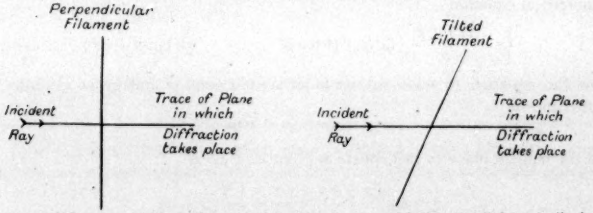


Fig. 2.

The distribution is not altered when the filament is tilted, so that it is no longer perpendicular to the direction of the original beam, and so it applies to the general case when such a beam falls on a parallel bundle of filaments (Fig. 3).


Perpendicular Filament
Incident Ray
Trace of Plane in which Diffraction takes place
Tilted Filament
Incident Ray
Trace of Plane in which Diffraction takes place
Fig. 3. The plane in which diffraction takes place is unaltered when the filament is tilted.

As has been shown, the light transmitted by a single filament is concentrated on the "transmission cone," and always makes an angle θ with the filament axis when the angle between the incident beam and the filament axis is θ. The trace of the transmitted and reflected light on a screen perpendicular to the filament axis is the circle ABC, whose centre is the projection of the filament axis on the screen (Fig. 4).

The trace of the diffracted light, however, is the straight line MBN touching the circle ABC at B, and the angle between the diffracted light and the filament axis is, in general, greater than that for the incident light. For instance, the light diffracted to the point M on the screen makes an angle of $\cos^{-1}(\cos\theta\cos\alpha)$ with the filament axis, where α is the angle of diffraction.

It must be remembered that the intensity of the diffracted light falls off rapidly as we depart from B, so that the angle of diffraction is always small.

A similar process takes place in the case of multiple reflections and transmissions between adjacent parallel filaments, and the effect of diffraction is thus always to increase the angle between the reflected light and the filament axis. It follows, therefore, that on comparing the light reflected from a pad of fine filaments with that from a pad of coarse filaments, more light would be concentrated between the reflection cone and the normal to the pad in the former case.

Also, as the angle of diffraction depends on the wave-length of the light, it might be expected that the lustre of a pad would be less for light of short wave-lengths than for long, and the colour of the pad would be bluer if the eye were on the normal to the pad than when on the reflection cone.

Neither of these effects has so far been observed, and so it seems as if this theory of diffraction is insufficient to account for any lustre effects.

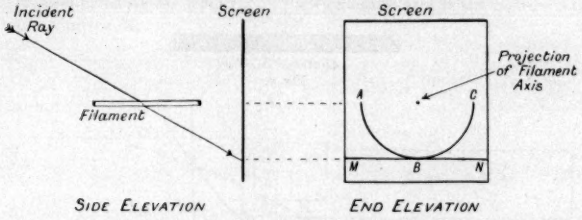


Fig. 4.

Method of Measuring Lustre

Discussion. Several instruments have been devised for measuring lustre, especially by Jones(1) and Schulz(2). The instrument designed by the latter has been marketed under the name of the Goerz Glarimeter, but it is understood that this is no longer manufactured owing to the small demand.

All these instruments compare the light "directly" reflected with that "diffusely" reflected from the test surface. The two are brought together into the field of view of a photometer, and the directly reflected light is reduced by some means until a balance is obtained (Fig. 5).

The actual angle of incidence and the angle between the directly and diffusely reflected beams are chosen arbitrarily in the different instruments.

The lustre of the surface is usually defined as the ratio of the directly reflected to the diffusely reflected intensity.

The value is, of course, dependent on the arbitrarily chosen directions in which the measurements are made, and no account is taken of the distribution of light at angles other than these two. For instance, if the diffusely reflected light was measured at various angles to the directly reflected beam, and plotted against this angle, then either of the two curves *A* and *B* in Fig. 6 would give identical lustre ratios, although the appearance of two such surfaces would be different.

Let us consider the details of the process when yarns or fabrics are compared visually for lustre. The yarn may be wound in some form, as for instance, on a bobbin, or it may be loose in the form of a hank. When wound on a bobbin, the lustre is apparent through the presence of high lights on the cylindrical surface when looking towards a light source, and two yarns are compared by making a

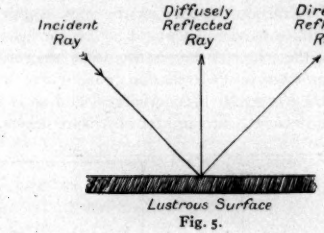


Fig. 5.

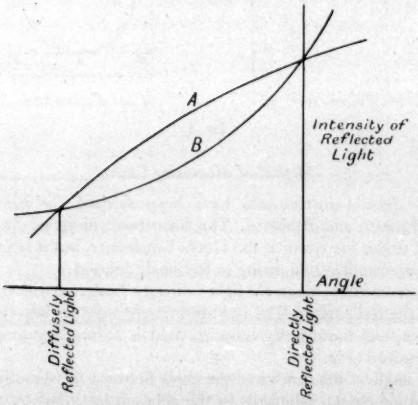


Fig. 6.

mental comparison of the two high lights. When in hank form lustre shows itself by the high lights at the curved ends of the hank, or in the variation of brightness of the straight sides when the hank is stretched and held in different positions. In the case of fabrics, lustre is estimated by examining the high lights when they are thrown into folds, and the variations of brightness as they are tilted about.

In all these cases the direction of the incident light and the direction of vision remain fixed, and the eye examines the contrast between various parts of the

surface differently inclined to the incident light. The variation in brightness is due to the different angles between the direction of vision and the reflection cone at different parts of the surface.

Lustre has not so far been defined as a definite physical quantity, and in looking for an improved method of measurement it is desirable that the conditions adopted in any instrument should conform as closely as possible to those existing when a visual comparison of lustre is made.

Description of photometer. In order to have an instrument in which any required conditions could be adopted a special photometer has been made and is shown diagrammatically in Fig. 7.

The photometer head H contains a Lummer-Brodhun photometric cube C, an achromatic eye lens A, and a stop B for locating the eye. The comparison surface S, which is illuminated by the lamp L_1, in the right-hand arm of the instrument, is seen *via* the mirror M.

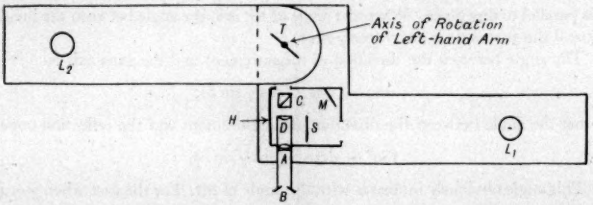


Fig. 7.

The lens D, which is additional to the optical system in the usual photometer head, is to bring the image of the test surface T into coincidence with the pupil of the eye located at B. This is in order to prevent the structure of the surface of T from being visible, and hence disturbing the ease of making the photometric balance.

The left-hand arm, which contains the lamp L_2 illuminating the test surface, is rotatable about a central vertical axis, and T is mounted over this axis. The mount is arranged so that T can be rotated separately about a vertical and a horizontal axis through the central vertical axis of the instrument, and it can also be rotated in its own plane.

Conditions chosen for measurement of reflection curve. The conditions already discussed under which the visual comparison of lustre is made can be imitated by keeping the angle between the two photometer arms fixed, and tilting the specimen mounted as a plane surface about some axis yet to be chosen. Different angles of tilt represent different positions on a fold or cylindrical surface, and the photometer enables the distribution of light in the high lights to be measured.

The two axes about which the specimen can be tilted are perpendicular, and parallel to the plane containing the incident beam and direction of vision which

we can call the photometer plane (Fig. 8). Whichever axis is chosen, the effect of tilt is to vary the angle between the direction of vision and the reflection cone. Hence the axes of the yarns or filaments under test must be set perpendicular to the axis of tilt. If they were set parallel to this axis, the effect of tilt would be merely to rotate them around their own axes, and the angle between the direction of vision and the reflection cone would be unaltered.

Take first the case when the axes of the yarns or filaments are parallel to the photometer plane and the surface is tilted about an axis perpendicular to this plane. If 2γ is the angle between the incident beam and direction of vision, then in the symmetrical position the normal to the test surface makes an angle γ with both. On tilting through an angle δ the angle of incidence is $(\gamma - \delta)$, the angle of reflection $(\gamma + \delta)$, and the angle between the direction of vision and the reflection cone is 2δ.

In the second case the axes of the yarns or filaments are perpendicular to the photometer plane in the symmetrical position, and they are then tilted about an axis parallel to this plane. When the angle of tilt is δ, the angle between the incident ray and the yarn axis is $\cos^{-1}(\cos\gamma \sin\delta)$.

The angle between the direction of measurement and the yarn axis is

$$180^\circ - \cos^{-1}(\cos\gamma \sin\delta),$$

so that the angle between the direction of measurement and the reflection cone is

$$180^\circ - 2\cos^{-1}(\cos\gamma \sin\delta).$$

This angle obviously increases with the angle of tilt. For the case when $\gamma = 45^\circ$, the values for different tilts are:

Angle of tilt	Angle between direction of measurement and reflection cone
0°	0°
± 10°	14°
± 20°	28°
± 30°	41·4°
± 40°	54°

In either case the lustre of the surface, or the extent to which light is concentrated on the reflection cone, is indicated by the peakiness of the brightness-angle of tilt curve.

Two typical curves for a lustrous cotton yarn are given in Fig. 9. The chief difference between them is that the first is not symmetrical while the second is. This is, of course, due to the dependence of the illumination of the surface on the angle of tilt. Where the tilt is about a vertical axis the illumination of the surface increases for one direction of tilt and decreases for the other, while for the tilt about a horizontal axis the illumination falls off equally for either direction of tilt.

In order to obtain a figure for the lustre of a surface we want some method of expressing the peakiness of these brightness curves. The asymmetrical curve does not lend itself readily to treatment, but the symmetrical curve can be treated by

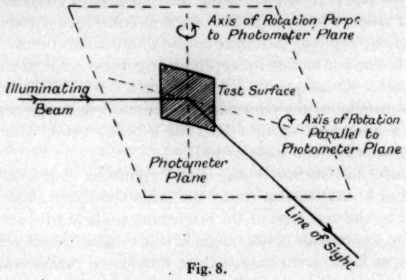


Fig. 8.

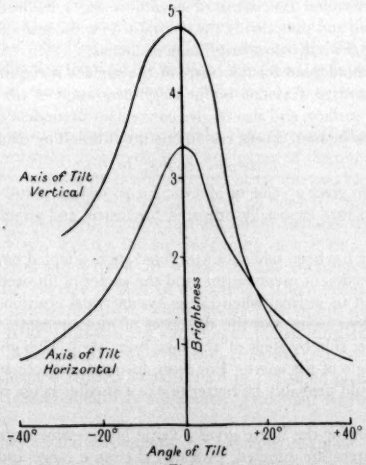


Fig. 9.

analogy with a curve of frequency distributions. On this analogy the brightness value represents the frequency with which a sample defined by the angle of tilt occurs, and the standard deviation of the curve defined by

$$\sigma = \sqrt{\{\Sigma \text{ brightness} \times (\text{angle of tilt})^2\}/\Sigma \text{ brightness}}$$

is a measure of its spread, and for this reason it seems preferable to use a tilt about the axis parallel to the photometer plane.

The reciprocal $1/\sigma$ is a measure of the peakiness of the curve.

Expression for lustre. There are some other points to consider before we can adopt a unit for lustre. The illumination of a theoretical matt surface is proportional to the cosine of the angle of incidence of the illuminating beam. It reflects light according to a cosine law so that its apparent brightness is the same from whatever direction it is seen. Consequently if such a surface were tilted about the axis of the photometer parallel to the photometer plane, its brightness-angle of tilt curve would not be a horizontal straight line but a peaky curve with ordinates proportional to the cosine of the angle of tilt.

The lustre of a test surface is due to its brightness under varying conditions relative to that of a matt surface under the same conditions, and so lustre ought to be estimated by the peakiness of the brightness-angle of tilt curve after dividing the ordinates by the cosines of the angle of tilt to give values relative to a matt surface. When, as is often the case, a large number of measurements have to be made, this process involves a large amount of arithmetic, and to avoid this the method is to determine the standard deviation for a theoretical matt surface, say σ_m, once for all and then divide the σ obtained on the test surface by this value without reducing the individual brightness ordinates.

The expression adopted for the lustre of the surface is required to give a value zero when the standard deviation of the brightness-angle of tilt curve is the same as that for a matt surface, and also to give convenient numerical values for the class of surface likely to be met. These conditions are fulfilled by using the expression

$$\text{Lustre} = 100 \log_{10} \{\sigma_m/\sigma\}.$$

The expression gives a value of about 2 for an ordinary dull cotton yarn, 8 for mercerised cotton yarn especially prepared for lustre, and about 30 for a lustrous rayon yarn.

So far, nothing has been said about the fixed angle adopted between the incident beam and the direction of measurement and the angles of tilt used. The test surface is arranged so that its normal when in the symmetrical position is inclined at 45° to both the incident beam and the direction of measurement, and angles of tilt up to 40° on either side by steps of 10° have been used. This gives nine points on the brightness-angle of tilt curve. For more lustrous surfaces such as rayon yarn dyed black, it would probably be better to use a smaller range of tilt with smaller steps.

The expression for the lustre gives a value of the same order whatever range of tilt or size of steps are adopted, provided the same range and size of steps are used in working out the value for σ_m.

In conclusion I wish to thank the Director and Council of the British Cotton Industry Research Association for permission for this paper to be published.

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DISCUSSION

Mr N. W. Yelland: I have listened to Mr Pelton's paper with great interest, particularly because we have been using a system of lustre measurement for several years in the Research Department of the Calico Printers' Association.

The methods which we have employed are very similar to those which Mr Pelton now describes, namely we use a special form of photometer to obtain curves, depending on the angular distribution of light reflected from the surface under test when it is illuminated by a single narrow pencil of light, and we obtain a measure of the degree of lustre of the surface by calculating the "peakiness" of the curve. It is therefore interesting to find that Mr Pelton has arrived at a similar method, guided partly by theoretical considerations regarding the reflection of light from textile fibres.

The reflection cone described in Mr Pelton's paper is, however, only formed with any degree of distinctness in the case of pads of parallel fibres having a very high glassy polish, such as artificial silk fibres. In the case of most textile yarns, and in all cloths, the reflection cone is absent, being completely obscured by fibre irregularities and twist, and by the effect of interlacing threads. Considerations based on the formation of the reflection cone therefore seem scarcely relevant or helpful in the case of light-reflection from textile surfaces in general; it appears that the latter should be regarded simply as surfaces exhibiting varying degrees of specular concentration of reflected light.

In his method of lustre measurement, Mr Pelton rotates the plane of the test surface so that its normal swings to different angles out of the photometer plane, on the ground that this method gives symmetrical lustre curves. We prefer the other method in which the normal is rotated in the photometer plane. Symmetrical curves can easily be obtained by this method (from surfaces which reflect symmetrically) in two ways. Firstly, the surface can be viewed along nearly the same direction as the illuminating beam, in which case the variation of illumination is compensated by the increase of area of the surface which sends light to the eye, this area being of course the patch whose image falls within the aperture of the eye-piece stop B. Also in this case the variation of illumination is symmetrical about the mid-position. Alternatively, the reflection from the test surface may be compared with the reflection from a matt surface in the same plane as in the Zeiss method of lustre measurement. A sufficiently good matt surface can be readily obtained in practice.

This method has several advantages; for example, it applies automatically the connection which Mr Pelton attempts by the calculation of σ_m the standard deviation of the curve for a matt surface. In connection with the latter method I should like to ask Mr Pelton whether it gives the same result as a proper point-to-point correction in the cases of lustre curves of every shape which can occur in practice. I would also like to ask whether Mr Pelton has made any systematic comparison between his lustre measurements and visual estimates of lustre. Agreement in this

respect is obviously essential in a sound system of lustre measurement. Practised judges agree with one another if the differences concerned are not too small.

The method of calculating lustre from the photometric curves seems rather laborious. Has Mr Pelton considered any more simple method of calculating the peakiness of the curves, and is it essential to treat them as frequency distribution curves?

The use of the logarithm in the calculation of the lustre figure probably also helps to make the lustre scale more uniform; i.e. equal increments of the lustre figure tend to correspond to equal increments of visual lustre throughout the scale range.

It is interesting to note that diffraction effects do not seem to account for the low lustre of fine-filament artificial silk. Is it not probable that the increased diffusion of light may be due to the increase of the number of slightly irregular surfaces at which the light is reflected or transmitted?

Capt. T. Y. Baker: I congratulate Mr Pelton on a very interesting and able paper. The work that is being done by the numerous Research Associations connected with industry is slowly convincing commercial firms that Physical Science can give them a great deal of help. Naturally progress in the "soft goods" trade is bound to be less rapid than in electrical and chemical industries, but, in time, it will be realised that the trade cannot progress without more and more research work being done.

Mr E. T. Hanson: The explanation of lustre by means of the "reflection" and "transmission" zones is probably true, and Mr Pelton has indicated in his very interesting paper the importance of the correlation between filament diameter and lustre.

Unless one has a rather precise knowledge of the form and optical properties of the filaments, I think the application of diffraction theory may be misleading. If the filaments are assumed to be truly parallel uniform cylinders we should, in effect, obtain a diffraction grating and we should expect to see the spectrum colours.

Mr J. Guild: Mr Pelton's paper is one which is of considerable interest to me from the point of view of its bearing on the general problem of measuring or evaluating gloss, a problem which arises in connection with a large variety of materials. It is highly desirable that sometime or other one definitely prescribed technique and one definite method of evaluation should be applied to the measurement of this property, whether it is found in textile materials, painted or varnished surfaces, paper, or other materials. Whether Mr Pelton's suggested basis for numerical evaluation is suited for such general application cannot be profitably discussed until similar results on a wide variety of other materials are available. His experimental method does, however, seem quite well suited to such general application, with the exception, which could be easily remedied, that as it stands it is only suitable for work on colourless materials. General applicability to coloured materials could be obtained by replacing the Lummer-Brodhun photometer head by a flicker disc. This would not involve any loss of sensitivity when dealing with

colourless substances, as compared with this present photometer, as the sensitivity of a properly designed flicker photometer is quite as high as that of the Lummer-Brodhun type even in the absence of colour-differences, while, of course, it is very much more sensitive than the latter when colour-differences exist.

As regards the problems more particularly dealt with by Mr Pelton, that is, those connected with the lustre of textiles of the artificial silk variety, it seems to me that the inferior lustre of fine fibres as compared with that of larger fibres has an obvious explanation in the character of the surfaces. As the author's photographs show, the assumption of a smooth transparent cylinder is only approximate, the fibres showing numerous surface markings and excoriations. If the magnitude and depth of these imperfections are similar in the different fibres, as is quite probable, then their importance in scattering light in directions other than the theoretical reflection cone, and so reducing the lustre, will be greater the smaller the fibre.

Mr Perry: I think Mr Pelton is to be congratulated on this paper. The measurement of lustre is becoming increasingly important and it is very necessary to plant the subject on a sound basis, the actual conception of what is called lustre or gloss not yet being at all a very precise one.

Is gloss purely the property of a material, or is it a characteristic of a material when illuminated and observed in a specific manner? Assuming a definite angle of incidence and distance of light source from the specimen under observation, by which latter the convergence or divergence of the incident light is determined, the reflection curve as determined by an appropriate photometer will in general show more than the one peak considered by Mr Pelton, while one such may or may not be predominant. This will result in an anomalous gloss effect, in the specification of which an essential datum is the orientation of the specimen relative to the direction of observation. Since the measurement of gloss has to serve a practical purpose it is a question yet to be decided and one upon which Mr Pelton's observations would be of much value, whether in the general case a single value can express with sufficient reliability the gloss of a fabric on any scale of measurement.

It is a practical desideratum that any instrumental measurement made should *inter se* show general agreement with naked eye estimation, and if a single consistent gloss value can be given by an unaided observer to such anomalous fabrics as those referred to above, some means of instrumentally simulating the mental integration which must form the basis of such an estimation would be required, such as, for example, rapid rotation of the specimen in its own plane.

Mr Pelton represents in Fig. 6 a state of affairs which qualitatively may certainly occur fairly frequently, but I presume that the curves given are purely hypothetical. I should like to ask Mr Pelton to what extent in his experience the curves *A* and *B* have been found in actual observation to vary for materials of ordinary single-peak reflection curves.

Mr M. O. Pelton (communicated): Mr Yelland's criticisms, coming from one with experience in another laboratory of the type of measurement in question, are especially valuable.

Dealing in turn with the various points he raises, I quite agree that in most textile yarns and cloths the distinctness of the reflection cone is very largely obscured. Even in materials of low lustre the reflection cone, duly modified by the effects of fibre irregularities and distortion produced by twist and interlacing threads, accounts for the observed photometric curves given by such a material. The difference between a dull cotton cloth and a pad of rayon yarn is one of degree only.

Mr Yelland suggests two alternative means for producing symmetrical reflection curves. In the first the surface is viewed along the same direction as the illuminating beam. It seems to me that here the photometer plane is indeterminate, so that there is no distinction between the normal swinging in or out of the plane.

The suggested connection with a matt surface by means of the quantity σ_m will not, in general, give the same result as a proper point-to-point correction, but the scale used is arbitrary and the practical problem is usually to detect small differences in a series of similar samples.

Visual estimates of lustre have been found to be in good agreement with the measured values for pads of yarn which give a single peak reflection curve. In the case of fabrics, the individual threads are often constrained in a series of sharp **V** shapes. This may lead with very lustrous cloths to a double peak reflection curve, and the σ values do not then agree with visual estimates and the method breaks down.

An alternative method of calculating the peakiness of the curves is the ratio Maximum Ordinate/Mean Ordinate.

One disadvantage of this expression is that the peak is a very sharp one for highly lustrous materials, and care has to be taken to ensure that a reading has been made at the true maximum.

Mr Guild suggests that the inferior lustre of fine filaments as compared with coarse is explained by the character of the surfaces. Since this paper was put forward some experiments have been made to try to test this point. Immersion of the fibres in a liquid of the same refractive index should obliterate the effect of all surface irregularities. When this is done marked differences are still apparent, and the material of the fine filaments appears to be more opalescent than that of the coarser.

In reply to Mr Perry, the orientation of the sample in the photometer in the case of textile materials is of prime importance, and the peakiness of the reflection curve gives the lustre in one plane only. In the case of a woven cloth there are two principal directions in which the measurement must be made.

It would be interesting to attempt to see if rotation of the sample in its own planes simulates the process of mental integration.

The curves shown in Fig. 6 are hypothetical. Quite large variations of this type have been found from fabric surfaces giving single peak reflection curves. The single peak may for instance be **V** or **U** shaped.

A RE-DETERMINATION OF THE MIXTURE CURVES OF THE SPECTRUM

By W. D. WRIGHT, B.Sc., A.R.C.S., D.I.C.

MS. received, 31*st January*, 1930. *Read and discussed*, 10*th April*, 1930.

ABSTRACT. The paper describes a method that has been developed for calculating the sensation curves and mixture curves from an average set of trichromatic coefficients and the standard luminosity curve, without recourse to any further experimental data. A complete table of colour mixture data is given. The practical value of different methods of colorimetry and the most desirable primaries for use as reference standards are briefly discussed.

Introduction

This paper is a continuation of one published in a somewhat condensed form in the *Transactions* of this Society* and of another given in a more extended report published by the Medical Research Council†. These papers described the results of colour vision experiments made by the author in the Technical Optics Department of the Imperial College of Science on behalf of the Physiology Committee of the Medical Research Council. The results obtained were derived from a large number of trichromatic colour mixture experiments by many observers, with the object of obtaining colour mixture data for a "normal" eye. Although sufficient experimental data for the specification of an average colour-matching eye were obtained, the method of calculating the mixture curves from that data had not been developed at the time the other papers were written.

I do not propose here to go into the details of the theory of colour mixing. My own conception of the problem is given in the Medical Research Council report, and I must assume that the reader has some knowledge of it or its equivalent. In this paper the spectral mixture curves are calculated from the trichromatic coefficients which have already been obtained. This involves knowledge of luminosity values, with which I have not dealt in detail in the previous papers and for which I have no reliable experimental data. It is probably needless to emphasise the importance of the mixture curves, but it may be worth while to point out that, with the coefficient curves alone, it is impossible to obtain the colour coefficients of a light which is defined by its energy distribution curve, the most fundamental physical definition that any radiation can have.

* W. D. Wright, "A re-determination of the trichromatic coefficients of the spectral colours," *Trans. Opt. Soc.* **30** 1928–29.

† W. D. Wright, "A re-determination of the trichromatic mixture data," *Medical Research Council, Special Report Series*, No. 139.

Theory

In the ideal case the mixture curves would be derived in the following manner. An observer with, we will assume, a "normal" eye both as regards colour and luminosity, makes a colour match of white and luminosity matches of the three primaries in order to obtain the relative luminosities of the trichromatic units of the primaries. By combining these quantities with the standard coefficient curves and the standard luminosity curve, the mixture curves can be computed. An example will illustrate most clearly the details of the process.

From the standard coefficient curves we have, say, for $0{\cdot}58\,\mu$ the result that

$$C = 0{\cdot}604R + 0{\cdot}414G - 0{\cdot}018B,$$

and by the luminosity matches, the relative luminosities of the three primaries may be in the following proportions,

$$L_R : L_G : L_B :: 38{\cdot}5 : 100{\cdot}0 : 3{\cdot}72.$$

The equation representing one T unit of $0{\cdot}58\,\mu$ expressed in terms of luminosity is then

$$L_c = 23{\cdot}2L_R + 41{\cdot}4L_G - 0{\cdot}07L_B,$$

from which it can also be concluded that the luminosity of one T unit of $0{\cdot}58\,\mu$ is proportional to $64{\cdot}5$, the sum of the three component luminosities. If in the white light spectrum we have that the relative luminosity at $0{\cdot}58\,\mu$ is $0{\cdot}776$, then we know that at this point the red is present in the proportion, in luminosity, of

$$\frac{23{\cdot}2}{64{\cdot}5} \times 0{\cdot}776 = 0{\cdot}280.$$

Similarly the green and blue are present in the proportions of $0{\cdot}497$ and $-\,0{\cdot}0008$ respectively. In the same way, similar values for other wave-lengths can be calculated and subsequently plotted to give the sensation curves. When plotted, the areas under the three curves give the proportions of the three primaries that go to make up white light, namely, in our case, $38{\cdot}5 : 100{\cdot}0 : 3{\cdot}72$, still in luminosity units. The mixture curves are derived from the sensation curves by increasing the ordinates of each separate curve so that the three areas are equal; thus, we should have to increase our red ordinates in the ratio $\frac{100{\cdot}0}{38{\cdot}5}$ and the blue by $\frac{100{\cdot}0}{3{\cdot}72}$. In this perfectly definite and rigid manner can the desired result, the mixture curves, be obtained in the ideal case postulated.

In the above example, it was taken for granted that, since the areas under the three sensation curves give the relative luminosities of the three primaries in white, then these areas must be proportional to the values obtained initially from the luminosity matches of the primaries. Thus we have two methods of determining the same values, and we have assumed they will give consistent results. This assumption is justified in our case as our data have been consistent throughout, inasmuch as we have used standard data and a "normal" eye. For another observer

with an eye not accurately the same as the standard, the results would have been inconsistent.

In the light of this example, it will be well to enunciate the problem more definitely. We have already a standard luminosity curve, and we have an average set of trichromatic coefficients which we propose to use. To determine the mixture curves the only data we need are the relative luminosities of unit quantities of the three primaries. In any given case this required information is in reality further subdivided; one part involving a colour match of white with a colorimeter to determine the trichromatic units; the other involving luminosity matches of the primaries. With an observer normal in both respects this information can be obtained directly. Such an observer would, however, be hard to find, but fortunately there are other methods available. For instance, a normal observer in colour matching could be employed to determine the trichromatic units by matching white and, immediately after, a person normal in luminosity could determine the luminosities of the three primaries on the same colorimeter. (It should be noted that where a single observer is referred to as having a normal eye, it would evidently be equally satisfactory if a group of observers whose average corresponded to the normal were used.) Again, the second operation, the luminosity matches, can be replaced by another method suggested by Mr Guild in the discussion of my last paper to this Society, in which no observer normal in luminosity is required. A colour match of the standard white is first made, and then similar filters to those employed in the colorimeter are inserted in turn in the beam of the white light and the resulting colours matched in luminosity by the respective primaries of the colorimeter. From the transmission curves of the filters and the luminosity curve of the white light, the relative luminosities of the three coloured beams can be derived. A similar, but more devious method, could be used with a colorimeter using spectral primaries, by making colour matches of the light transmitted through three filters of known transmission factors. Three equations, with the three required luminosities as the unknowns, would be obtained and the desired solution could be readily derived.

There is yet another method by which the quantities we want can be determined, and it differs from the others in that no further experimental data are required other than the standard luminosity and coefficient curves. Suppose we assume three values for the relative luminosities of unit quantities of the three primaries, and calculate the corresponding sensation curves. In general the areas under the three curves will not agree with the proportions of the assumed luminosity values. In that case another set of assumed values could be tested, and a third and so on. In this manner it should be possible to alight on or near the one set which would give a consistent result. If a solution could be found in this way, only by a rational rather than a haphazard process, the result would be as valid, and could be made more accurate, than that obtained by some experimental method. It might appear at first sight that the element of luck would have to enter in before a solution was obtained and, at the time the previous papers were written, I was doubtful as to the practical application of the method, as it appeared very laborious and

unlikely to lend itself readily to a logical attack. I therefore let the matter rest for the time being, but subsequently found the problem neither so haphazard nor as lengthy as I had anticipated. There is a further point which increases the value of this method. In the set of mixture curves finally standardised, the luminosity curve will indirectly be re-standardised. In all of the experimental methods suggested, some observational and experimental errors must exist, and to this extent it might happen that two slightly different luminosity curves would be standardised. To prevent this, a correction would have to be made on paper to make all the standards accurately consistent. In other words, the method used in this paper will almost certainly have to be employed in making final adjustments and corrections, if experimental results are employed in standardising the mixture curves.

The systematic process that was used can be described quite briefly. The problem is immediately simplified when it is realised that the blue sensation is of very low luminosity as compared to the red and green. It is, therefore, only necessary to choose a roughly correct value for the blue luminosity in the first place, and keep it fixed whilst varying the proportion of the red to the green. After one or two sets of assumed values for the red and green have been tested it is possible to select the approximate region where the red luminosity should be, assuming that the green is kept constant at 100·0. For each set of assumed values the sensation curves are calculated and plotted, and the areas under the curves measured. Disregarding the blue data for the present, the ratio between the derived green and red areas is plotted against the assumed red luminosity, and in addition the ratio between the assumed green and red luminosities is plotted, also against the assumed red luminosity. The intersection of these two curves occurs at that red luminosity that will give consistent data. In the same manner the blue luminosity is found whilst the red is kept constant. This procedure is only justified because adjustment of the blue luminosity has very little effect on the red curve, owing to its relatively small value. If the blue had been found first and the red subsequently, then the blue would have been greatly in error after the proper red value had been determined. Even with the method used, further small corrections had to be made before the final data were obtained.

The calculations were made with the same primaries that were used in determining the trichromatic coefficients, namely, 0·65μ, 0·53μ and 0·46μ. Fig. 1 shows the resulting sensation curves. The areas under these curves are in the following proportions:

red 38·5; green 100·0; blue 3·72;

which are the same as the originally assumed luminosities. The red value can be relied on to within an accuracy of 0·2 per cent., the blue to 0·6 per cent. The accuracy obtained depends almost entirely on the scale and accuracy used in plotting the curves and could, therefore, be made higher if desired. In summing the areas, the portions below the zero line are, of course, counted as negative areas. The luminosity data used referred to a source having an energy radiation similar

to that of a black body radiating at 4800° K., the same as that used as the standard white in the colour matching experiments.

It may be well, here, to forestall some criticism that is almost certain to be directed against my description of the curves in Fig. 1 as "sensation" curves. I am well aware that these curves cannot legitimately be called sensation curves; that is, they do not represent the actual sensation responses of the eye. They cannot, because they contain negative quantities. The curves do, however, represent the same facts as the true sensation curves, even though they are not referred to the fundamental sensation primaries. My main justification for the use of the term

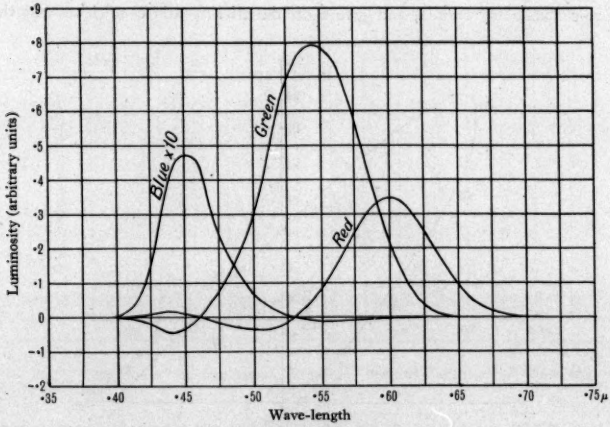

Fig. 1. Spectral mixture curves in luminosity units. (Primaries—red 0·65 μ, green 0·53 μ, blue 0·46 μ, white 4800° K.)

is that of simplification. The most correct description of the data would be "the spectral mixture data expressed in terms of luminosity." To have used this expression several times in the previous paragraphs would have been very clumsy, and I think the description I have used is sufficiently accurate for the purposes of this paper. I do not suggest, however, that these curves should in general be described as sensation curves.

Once the correct luminosities have been found for one set of primaries, they can be calculated immediately for any other set by making a few arithmetical transformations. Hence, as any primaries can be used, it is important to decide to which set it is most desirable to refer the final results. In discussing my last paper Mr Guild suggested that it would have been better if I had expressed my spectral trichromatic coefficients relative to the primaries red (0·70 μ), green

(0·5465 μ) and blue (0·436 μ). The value of these primaries is that they are readily available in the laboratory for calibration purposes without resort to elaborate spectroscopic apparatus. Further, they had been used at the National Physical Laboratory for some time, and were in use in a number of commercial laboratories. Under these circumstances my results would undoubtedly have been of more immediate practical value if they had been expressed in these terms, yet there are objections to such primaries, and I made a comment to that effect at the time. My principal objection was that they were unsuitable for employment as the actual primaries of a colorimeter, with the result that at no time could a colorimeter be designed to give standard colour measurements directly. Nevertheless, I decided to re-calculate my results, and give both the trichromatic coefficients and the

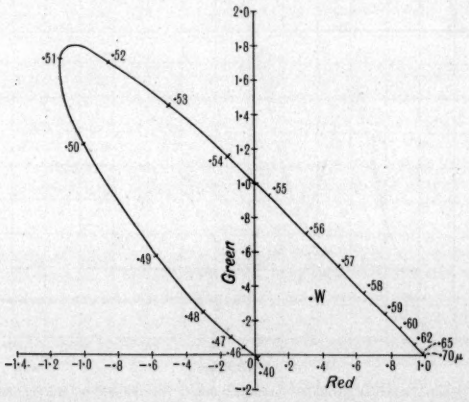

Fig. 2. The colour triangle referred to, red 0·70μ, green 0·5465μ, blue 0·436μ as primaries.

mixture curves relative to the National Physical Laboratory primaries. Although I made the necessary calculations, it will be seen that I have not made any changes in the primaries in presenting the results of this paper; I think it will be desirable to go into the reasons for this step in some detail.

In the first place the spectral locus in the colour triangle adopts the shape shown in Fig. 2, when plotted relative to the N.P.L. primaries. Now, in a sense, one colour triangle gives just the same results as another, but, on the other hand, some may be easier to use than others and be more accurate. One objection to Fig. 2 is, that the area of the colour field outside the triangle is greater than that inside; hence the number of colours with negative coefficients is very great. In a colorimeter this would be a very serious objection, and even for arithmetical work is an undesirable property. Further, although for no known colour triangle does

a given displacement in any part of the field correspond to a constant number of perceptible colour differences, yet some triangles are better in that respect than others. This one, it seems, is rather bad, as the spectral colours around 0·52 μ, for instance, are much too far from the white point W, since they are colours of low saturation when compared to the red or blue ends of the spectrum. This point, again, might not appear to be of great significance, at least for a commercial standard, but it makes the solution of colour mixture problems by geometrical methods more complicated, as the accuracy that could be placed on the results would vary greatly in different parts of the colour field.

There still remains, however, the very definite advantage that the N.P.L. primaries can be readily obtained in the laboratory for calibration purposes. But

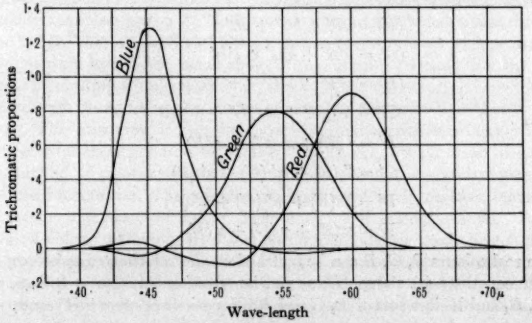

Fig. 3. "Equal-area" mixture curves. (Primaries—red 0·65 μ, green 0·53 μ, blue 0·46 μ, white 4800° K.)

it appears that this advantage can be retained for any other set of primaries at the expense of a very small amount of time and trouble. Consider what is involved in calibrating a colorimeter with these primaries. Each primary and white is matched in turn in the colorimeter, and four equations of the form

$$\left.\begin{aligned} R &= \alpha R_1 + \beta G_1 + \gamma B_1 \\ G &= \alpha' R_1 + \beta' G_1 + \gamma' B_1 \\ B &= \alpha'' R_1 + \beta'' G_1 + \gamma'' B_1 \\ W &= 0{\cdot}33 R_1 + 0{\cdot}33 G_1 + 0{\cdot}33 B_1 \end{aligned}\right\} \quad \ldots\ldots(1)$$

are obtained, where R, G and B are the suggested standard primaries. R_1, G_1, B_1 are the instrument primaries, W is the standard white and α, β, γ are coefficients. These equations can then be solved to give R_1, G_1, B_1 and W in terms of R, G and B (equations 4), and with this new set of equations all subsequent colour matches can be transformed to give results in terms of the three standard primaries.

This calibration process is not a frequent occurrence; the intervals between successive calibrations will depend on the constancy of the colorimeter being used and the accuracy with which the relevant experimental conditions are controlled. An interval of about a week would probably be frequent enough for average conditions.

Suppose, now, that our standard primaries are not the ones that are available in the laboratory, but are some other sensations, possibly hypothetical, that have been chosen by their position in the colour triangle. The standard spectral coefficients will be given relative to these primaries and the real N.P.L. primaries R, G, B will be given relative to the new standard primaries R', G', B' by the equations (2). These can be transformed to give R', G', B' and W in terms of R, G, B as in equations (3).

$$\left.\begin{aligned}(R) &= aR' + bG' + cB' \\ (G) &= a'R' + b'G' + c'B' \\ (B) &= a''R' + b''G' + c''B' \\ W &= 0{\cdot}33R' + 0{\cdot}33G' + 0{\cdot}33B'\end{aligned}\right\} \quad \ldots\ldots(2).$$

$$\left.\begin{aligned}R' &= l\,(R) + m\,(G) + n\,(B) \\ G' &= l'\,(R) + m'\,(G) + n'\,(B) \\ B' &= l''\,(R) + m''\,(G) + n''\,(B) \\ W &= x\,(R) + y\,(G) + z\,(B)\end{aligned}\right\} \quad \ldots\ldots(3).$$

The real colours R, G, B can be matched on the colorimeter as before, to give the four equations (1) above. These can be transformed, also as before, to give R_1, G_1, B_1 and W in terms of R, G and B. Equations (4) give this result.

$$\left.\begin{aligned}R_1 &= \lambda R + \mu G + \nu B \\ G_1 &= \lambda' B + \mu' G + \nu' B \\ B_1 &= \lambda'' R + \mu'' G + \nu'' B \\ W &= x_1 R + y_1 G + z_1 B\end{aligned}\right\} \quad \ldots\ldots(4).$$

The use of the round brackets in equations (2) and (3) is in order to distinguish between different unit quantities of the same colours, as we are dealing with the same colours expressed in two distinct trichromatic systems. In fact, it is the relation between the two systems that must be found in order to make use of this method of calibration. It is given directly by the last equations of (3) and (4). Here we have the same colour, white, represented relative to the same primaries in the two equations, the only difference being in the units that have been taken in the two cases. To find the relation, it is only necessary to equate the total quantities of corresponding primaries in the two cases, so that

$$x\,(R) = x_1 R; \quad y\,(G) = y_1 G; \quad z\,(B) = z_1 B;$$

whence

$$R = \frac{x\,(R)}{x_1}; \quad G = \frac{y\,(G)}{y_1}; \quad B = \frac{z\,(B)}{z_1} \qquad \ldots\ldots(5).$$

These equations, together with the values for (R), (G), (B) from equations (2), can be combined with equations (4) by straightforward substitution to give expressions for R_1, G_1, B_1, the instrument primaries, in terms of R', G', B', the standard primaries. The remainder of the calculations to express any colour matched on the colorimeter follows exactly the same lines as in the case when the primaries were real physically reproducible radiations.

It is thus evident that we can use any primaries we wish and still retain the advantages of the N.P.L. primaries for calibration purposes. There is the possible objection that more work is involved, but it is easy to show that the additional work is negligible. Equations (2) and (3) would be supplied by the standardising laboratory and would, therefore, involve no extra routine work; equations (1) and (4) have to be found in either case, so that the only fresh calculations that have to be made are those giving R, G, B from equations (5) and (2), and their substitution in (4). This is a matter of but a very few minutes' work and, as the whole calculations only have to be made about once a week, it is clear that the fear of additional computing is unjustified.

Armed with these facts, the choice of possible primaries is evidently greatly increased. They can now, in fact, be chosen on their merits as primaries and not on indirect grounds of practical availability. The choice, I think, must be governed by the method of colorimetry that is or will be adopted as standard practice in commercial laboratories. The possible methods are four in number, namely, (*a*) visual colour matching, including trichromatic and monochromatic methods, (*b*) physical colour matching, (*c*) visual spectrophotometric methods, (*d*) physical spectrophotometric methods. In discussing the relative merits of these methods, it will simplify matters if we assume that colorimetric data have already been standardised. The main difficulty with method (*a*) is the difficulty of obtaining observers with a "normal" colour-matching eye. For reliable colour specifications this method is going to be very difficult to put into practice, although for experimental and investigational work it is a very valuable tool. Method (*b*) at present seems almost, if not quite, as unfavourable for accurate colour recording as (*a*). I am referring, of course, to instruments using photo-electric cells, with or without colour filters, giving response curves similar to the three sensation curves. The great difficulty of reproducing similar photo-cells, of maintaining the response curve of a given cell unchanged with time and varying conditions, the very small currents and high amplification involved, indicate the extreme complications that are entailed in such methods. Method (*c*) is good for giving complete information as to the colour qualities of the object under test, but for dark opaque objects the accuracy is likely to be too low for even tolerably accurate results, more particularly in the blue region of the spectrum. Further, the time taken to secure the required information is undesirably long, and a good deal more information is obtained than is often needed. In method (*d*), on the other hand, I believe we have the salvation of colorimetry in sight, if not immediately at hand. The possibilities depend, of course, on the further development of the photo-cell, both as to sensitivity and reliability, but the need of any great accuracy of reproducibility can

be removed almost entirely by using what amounts to the substitution principle. One type of instrument designed on these lines has been described by Professor A. C. Hardy*. With the photo-cells that are available to-day, satisfactory instruments can undoubtedly be built, although the technique involved has still to be developed; with the improvements in photo-cells that are bound to come, this seems to be a very promising solution to colorimetric problems. The physical spectrophotometric scheme gains over the visual method in the matter of time and in the fact that photo-cells with increasing sensitivity in the blue can be used.

If this outline of the position is, in the main, correct, it will be evident that those primaries should be chosen as standards that are most convenient for use with the method of colorimetry described under section (*d*) above. For this, a hypothetical set giving an all-positive series of mixture curves would undoubtedly be most suitable, as then the smallest number of operations to transform spectral distribution curves into trichromatic units would be required. Although I feel that this is the goal to aim at, I have not given my results relative to such primaries because their final selection depends on additional, though minor, factors; such, for instance, as approximately equal colour discrimination for equal displacements in the colour triangle. To find the most satisfactory set of primaries, additional investigation is necessary, and until this has been made I do not think there would be much value in giving the mixture data in terms of any chance set of "all-positive" primaries. For this reason I decided that the best I could do at present was to give my results relative to the same primaries that I had used in the experimental work, namely, $0{\cdot}65\mu$, $0{\cdot}53\mu$ and $0{\cdot}46\mu$. But although it is, I believe, sufficiently evident from the foregoing discussion, I wish to emphasise the fact that I have no personal preference for these primaries, apart from their convenience as the primaries in a colorimeter, and I do not consider them the best to use as standards.

The complete results are given in the accompanying table. I thought it would be convenient for reference purposes if all the mixture data were collected together, and I have accordingly reproduced the trichromatic coefficients that were given in the last paper. To avoid any possible confusion, I have also given the energy data and luminosity values that were used for the "white." The energy curve was calculated for a black body radiation of 4800° K. by Planck's formula, using a value of $c_2 = 14{,}330$; the calculations were made with the aid of tables given by W. W. Coblentz†. The mixture data expressed in terms of luminosity, the equivalent of the sensation curves, are given and lastly the "equal-area" mixture data are tabulated. Figs. 1 and 3 show the same values graphically.

* A. C. Hardy, "A recording photoelectric colour analyser," *J.O.S.A.* **18** 1929 (96).

† W. W. Coblentz, *Bureau of Standards, Bull.* **15** 1920 (617).

Wavelength in μ	Trichromatic coefficients			White light energy radiation	White light luminosity	Mixture data in luminosity			"Equal area" mixture data			Wavelength in μ
	Red (0·65 μ)	Green (0·53 μ)	Blue (0·46 μ)			Red	Green	Blue	Red	Green	Blue	
·400	·052	− ·048	·996	·563	·0002	·0004	− ·0010	·0008	·0010	− ·0010	·022	·400
·410	·051	− ·047	·996	·595	·0007	·0014	− ·0033	·0026	·0036	− ·0033	·070	·410
·420	·049	− ·046	·997	·628	·0025	·0047	− ·0115	·0093	·0122	− ·0115	·250	·420
·430	·045	− ·043	·998	·658	·0076	·0116	− ·0288	·0248	·0301	− ·0288	·667	·430
·440	·036	− ·037	1·001	·687	·0158	·0156	− ·0414	·0416	·0405	− ·0414	1·120	·440
·450	·021	− ·024	1·003	·715	·0272	·0103	− ·0304	·0473	·0267	− ·0304	1·272	·450
·460	·000	·000	1·000	·739	·0443	·000	·000	·0443	·000	·000	1·191	·460
·470	− ·031	·057	·974	·762	·0693	− ·0102	·0486	·0309	− ·0265	·0486	·830	·470
·480	− ·094	·182	·912	·783	·109	− ·022	·110	·0206	− ·0571	·110	·554	·480
·490	− ·170	·420	·750	·802	·167	− ·029	·184	·0122	− ·0753	·184	·328	·490
·500	− ·233	·772	·461	·820	·265	− ·034	·292	·0065	− ·0883	·292	·175	·500
·510	− ·207	1·002	·205	·836	·421	− ·036	·453	·0034	− ·0935	·453	·091	·510
·520	− ·111	1·049	·062	·848	·602	− ·026	·625	·0014	− ·0675	·625	·038	·520
·530	·000	1·000	·000	·860	·740	·000	·740	·000	·000	·740	·000	·530
·540	·123	·901	− ·024	·869	·828	·041	·788	− ·0008	·106	·788	− ·022	·540
·550	·232	·797	− ·029	·877	·872	·0880	·785	− ·0011	·228	·785	− ·030	·550
·560	·354	·676	− ·030	·883	·878	·147	·732	− ·0012	·382	·732	− ·032	·560
·570	·480	·543	− ·023	·889	·845	·215	·631	− ·0010	·558	·631	− ·027	·570
·580	·604	·414	− ·018	·892	·776	·280	·497	− ·0008	·727	·497	− ·022	·580
·590	·720	·290	− ·010	·894	·676	·330	·346	− ·0005	·856	·346	− ·013	·590
·600	·811	·196	− ·007	·895	·565	·347	·218	− ·0003	·901	·218	− ·008	·600
·610	·881	·124	− ·005	·895	·450	·329	·121	− ·0002	·855	·121	− ·005	·610
·620	·929	·075	− ·004	·893	·340	·281	·059	− ·0001	·730	·059	− ·003	·620
·630	·966	·037	− ·003	·891	·236	·215	·021	− ·0001	·558	·021	− ·002	·630
·640	·988	·014	− ·002	·887	·155	·150	·0055	·000	·390	·0055	·000	·640
·650	1·000	·000	·000	·882	·095	·0950	·000	·000	·247	·000	·000	·650
·660	1·006	− ·006	—	·877	·0535	·0542	− ·0007	—	·141	− ·0007	—	·660
·670	1·009	− ·009	—	·871	·0279	·0285	− ·0006	—	·074	− ·0006	—	·670
·680	1·011	− ·011	—	·864	·0147	·0151	− ·0004	—	·0392	− ·0004	—	·680
·690	1·013	− ·013	—	·857	·0070	·0072	− ·0002	—	·0187	− ·0002	—	·690
·700	1·015	− ·015	—	·849	·0035	·0036	− ·0001	—	·0094	− ·0001	—	·700
White (4800° K.)	·333	·333	·333	—	—	38·5	100·0	3·72	·333	·333	·333	White (4800° K.)

DISCUSSION

Mr Perry: Mr Wright's paper forms a valuable contribution to the normalisation of colour which is now in process. Two things only can impede progress toward the desired end; namely the lack of observational data, this being certainly an important impediment which, however, time alone can remove, and the lack of a unified system or conventional method of stating results and mean standard data. In regard to the latter question, since the establishment of fixed points in the colour field is largely a matter of obtaining a general world-wide consensus of opinion, some time will inevitably elapse before the desired state of affairs is brought about. It will be clear, therefore, that present-day observations should be carefully defined in all particulars and should also be as nearly as possible reduced to one system in order to facilitate any possible reconversion of the results at a later date. In this respect I should like to suggest that as the adoption of a standard energy distribution is an important matter in the present state of things, the uniform energy spectrum has strong claims to be considered standard. It affords in the first place a fixed basis upon which to operate and has, moreover, the advantage that it facilitates calculations of a more purely physical and objective nature. It should also be remembered that an investigator in later years on referring to our contemporary colorimetric literature would be a little disturbed to find the standard white variously referred to and varying at least between 4800° and 5000° K. effective colour temperature, in spite of our desire for standardisation and the work that is in progress. The adoption of the uniform energy spectrum would unify present-day procedure without imposing any fresh standards.

In connection with the spectrum locus as plotted in Fig. 2 and on the question of the occurrence of negative coefficients in actual colorimetry when the primaries 7000, 5461 and 4359 A. are employed, it is remarkable how very rarely a negative coefficient enters into the specification of a colour, this being a fact which, except for the explanation possible for it, would certainly be a little surprising.

Mr J. Guild: This is the third of a group of papers which Mr Wright has presented to the Society in which he has made an important contribution to the available data on colour vision and colorimetry. The first paper described the apparatus which Mr Wright designed for the work; the second gave the results of the measurements carried out with it, while this paper contains further deductions from these results. It is the second paper, therefore, which contains the actual contribution to experimental knowledge, as embodied in the trichromatic coefficients (unit equations) for the spectrum given therein. In discussing that paper at the time I was unable to make any comment on the actual results, as Mr Wright had expressed them in terms of his own working primaries, and the paper had not been in my hands long enough for me to transform them to the primaries used at the N.P.L. so as to compare them with the values which we use there*. Mr Wright has

* For the last few years we have employed at the National Physical Laboratory a set of trichromatic coefficients, and mixture curves based on them, embodying the observations of seven observers carried out on purified spectral colours using a Guild colorimeter. These curves have been computed

now given his trichromatic data in terms of the N.P.L. primaries in Fig. 2 of the present paper, though abstaining, for reasons which I will discuss presently, from including these in his tables. I have compared these with my own figures at various critical parts of the chart and am pleased to say that no discrepancies exceeding the colour limen in the neighbourhood were found at any of the points checked. This agreement adds enormously to the value to be attached both to Mr Wright's data and our own, because it must be remembered that the two determinations were made by different groups of observers employing entirely dissimilar apparatus. It shows in a very striking manner that, provided adequate attention is given to the standardisation of the auxiliary apparatus and to such points as field size, these determinations can be carried out with a much higher degree of accuracy and reliability than is still supposed, in many quarters, to be the case, and that a comparatively small group of observers is sufficient to reduce the effects of personal variations of vision to quite small amounts.

It is thus clear that Mr Wright's trichromatic coefficients, which are, so far, the only published set based on modern experimental work, can confidently be regarded as a very close approximation to the properties of an average eye.

With regard to the "mixture curves" deduced from them (Figs. 1 and 3 of the present paper) I am by no means so happy. I have not had time available since the paper came into my hands to convert these to our primaries, so cannot say directly whether they agree or otherwise. But treating them simply on their own merits as a deduction from the author's previous data, the method he has used is open to serious objection. His criterion would be perfectly sound if his data were *absolutely* accurate and *absolutely* consistent with the assumed normal visibility curve. In practice, however, it is invalidated by the fact that any experimental results are only approximate, and certain finite tolerances are associated with all the numerical data inserted in the mathematical relationships. To develop this point in detail here would unduly expand this discussion, and, for the present purpose, I need only point out that errors in the assumed values of the trichromatic coefficients, which may be sub-liminal as regards their colorimetric significance, may give, in the values deduced by Mr Wright's procedure for the luminosity coefficients of the primaries, errors which are greatly in excess of any reasonable tolerance in these quantities. This is particularly the case as regards the blue primary, owing to the manner in which the plus red and minus green ordinates at the blue end of the spectrum enter into the calculation, and the relatively large luminosity coefficients of these as compared with that of the blue primary. It is easy to show that errors in either the red or green curve in this neighbourhood, which are quite sub-liminal in the colorimetric determinations, may give rise to quite large errors, say 20 %, in the deduced value of L_B. The resulting mixture curves, while fulfilling Mr Wright's criterion of complete consistency when applied to the "white light" stimulus to

relative to the N.P.L. standard white light (which has also been used by Mr Wright). They have given excellent agreement between direct colour measurement and results computed from spectrophotometric data, in all cases for which they have been tested in the course of our work. I have delayed publication of these, however, until International agreement on a standard white light is arrived at, in order that the published results may apply directly to such white.

which he has fitted them, may give rise to serious errors in calculating colours due to other types of stimulus.

It is necessary, in order to get reliable mixture curves, to start with independently determined values for the luminosity coefficients of the primaries, employing these to calculate the mixture curves on a luminosity basis so as to fit the assumed spectral luminosity curve which it is proposed to use. If the areas of the three curves thus obtained do not have the same proportions as the luminosity coefficients, the initial data must be examined to see what alterations in *any* of the experimental quantities involved are required to obtain consistency, taking care that all such alterations are within the experimental uncertainty corresponding to each quantity. In this way completely consistent curves will be obtained which not only fit the criterion adopted by Mr Wright, but which are accurate to within the errors of experiment in respect to *all* the quantities involved.

If consistent curves cannot be obtained without altering either the luminosity measurements or the colorimetric measurements by amounts which exceed the experimental tolerances in either, this points to the presence of some systematic error in some of the processes and must be traced to its origin and got rid of before any value whatever can be put on the final results. By having no experimental check on his luminosity values, Mr Wright fails to satisfy all the necessary conditions, and his mixture curves may not be the best correlation between his trichromatic coefficients and the assumed standard visibility curve.

Thus, while Mr Wright's trichromatic coefficients, and the colour chart based on them, can safely be accepted as representing the truth to a high degree of accuracy, the same reliability cannot be attributed to his mixture curves without confirmatory evidence, not included in the present paper.

With regard to the question of reference primaries, I am sorry that Mr Wright, after very nearly coming into line with the N.P.L., should have been diverted from this intention by considerations of a purely sentimental character which are not really relevant to the problem of standardisation. He objects that the N.P.L. primaries:

(*a*) Are unsuitable for direct use as the primaries of actual colorimeters.

(*b*) Involve the introduction of negative coefficients for a very large area of the colour chart.

(*c*) Give an elongated form to the colour chart which detracts from the accuracy of graphical calculations of colour mixture problems.

Taking the last point first, in plotting Fig. 2, Mr Wright has accidentally adopted the least advantageous method by taking Red and Green for the coordinate axes. For problems in which it is desired to have the complete chart it is preferable to plot the Blue and Green coefficients. The resulting diagram is then much less elongated. Further modifications can be obtained by using different linear scales for the two axes. For many problems only portions of the chart are required, and I showed in a paper which I presented to the Society some years ago on the Geometrical Solution of Colour Mixture Problems* that in such cases it was

* *Trans. Opt. Soc.* **26** 1924–5 (139).

possible, by suitable choice of coordinates, to obtain an accuracy of graphical calculation far in excess of colorimetric requirements without employing large sheets of graph paper. The great beauty of the rectangular coordinate plot, as compared with the more symmetrical colour-triangle of Maxwell, is that it lends itself so readily to such manipulations.

With regard to the first two of Mr Wright's objections, to answer these would involve going into the whole question of the considerations which should govern the choice of working primaries and reference primaries at a length which is out of the question here. I shall take an early opportunity of offering to the Society a short paper dealing with the various aspects of the matter as they appear to me, and as they have governed our practice at the N.P.L. In the meantime all I can say in a few words is that very careful consideration was given to the selection of primaries at the N.P.L., both as regards the working primaries used in the Guild colorimeter, and as regards the reference primaries adopted. Mr Wright's suggestion of employing a set of reference primaries other than the three radiations used for calibrating the working primaries was foreshadowed in another of my own papers*, and a complete solution of the necessary transformations is given there. At that time I had not gone so thoroughly into some of the practical aspects of such problems as I had to do later, and was favourably disposed to the idea of proceeding on those lines. Later on, however, I concluded, for reasons which I will give in the proposed paper, that the procedure was undesirable as an integral part of a system of measurement. The transformations involved are, of course, perfectly sound, and for certain purposes the process is very convenient. We have used it successfully in various investigations and sometimes employ it in certain test work, but it ought not to be introduced as part of the framework of a standard system of measurement. As Mr Wright has, apparently, already carried out the numerical work involved in converting his results to the N.P.L. system, I hope it will be possible for him to include a table of these figures in addition to those relating to his working primaries. If he does so it will be desirable to state, with reference to the mixture curves, whether each set was independently deduced from the trichromatic data expressed in its own system of primaries, or whether the mixture curves for the N.P.L. primaries were obtained from those for the working primaries by direct application of the transformation equations to the ordinates of the latter.

I would like to close, as I started, on a note of appreciation of the skilful work involved in Mr Wright's contributions to this subject. The criticisms I have made on the present paper are offered because I think Mr Wright's work is worth criticising.

Mr W. D. Wright (communicated): The suggestion which Mr Perry makes, and which has been put forward in other quarters, for a uniform energy spectrum as the standard of reference for colorimetry, is one that is rather attractive as a solution to the problem, more particularly from the theoretical point of view and

* "On the Transformation of Trichromatic Mixture Data: Algebraic Methods." *Trans. Opt. Soc.* **26** 1924–5 (95).

from the standpoint of colorimetric calculations. The great drawback, I think, is that a source with such an energy radiation cannot be provided in any easy manner in the laboratory, nor does it correspond very closely to the average spectrum of daylight. To my mind, one essential feature of a standard white is reproducibility in the laboratory, so that direct comparison of colours can be made under standard conditions. It is not difficult to imagine considerable confusion arising if such a condition did not exist, as cases would occur where two colours were, by computation, the same for an equal energy spectrum, but which, for all practical sources of energy, would not match. For this reason I prefer some approximate black body radiation such as that provided by the N.P.L. standard.

Referring to Mr Guild's remarks, I am very pleased to hear that the trichromatic coefficients that I have obtained are in such good agreement with those determined at the N.P.L. It is naturally very gratifying to have my results confirmed in this way, and I hope the close agreement will help to accelerate the process of standardisation.

Mr Guild has provided a fair criticism of the method I have used to obtain, theoretically, the mixture curves from the experimentally determined coefficients given in my last paper. His argument is sound, and it is evident that some modification of the mixture data will almost certainly be necessary at some time in the future. If it should happen that the additional results given here prove to be of little permanent value, I hope the description of the method and the discussion that has been raised will have been worth while.

Although no great weight can be attached to the comparison, it may be of interest to compare the luminosities of the primaries as calculated in this paper with those found experimentally and quoted in the previous paper. These latter were obtained from luminosity measurements made under conditions which were not standard, but which, nevertheless, have some value. The two sets of results are given below.

	Relative luminosity of primaries (units on spectral basis)		
	Red	Green	Blue
Average of seven observers	66·6	100·0	5·2
Results from present paper (after changing units)	65·0	100·0	4·4

Considering the wide variations amongst individual observers, the red luminosities are in very good agreement, whereas the blue values differ considerably relative to the individual variations. This fact gives further support to Mr Guild's argument, though of course the experimental results cannot be relied on to a very great extent.

With regard to the choice of primaries, I am still of the opinion that a hypothetical set giving an all-positive series of mixture curves would be best, not from considerations of a sentimental character, but rather from the practical aspect of

convenience in arithmetical calculation. As I point out in this paper, I base this conclusion on the assumption that by far the larger part of the colour measurements of the future will be made by some spectrophotometric method. The conversion of such results into trichromatic units will definitely be simpler if the mixture curves are all-positive, and I believe such curves would cause less confusion to the average user of them. Unless, therefore, there are further arguments in favour of the spectral primaries, I cannot help but conclude that for most purposes a hypothetical set of primaries would be more convenient. I shall, however, await with great interest the publication of Mr Guild's proposed paper on the subject.

Wave-length in μ	Trichromatic coefficients		
	Red ($0{\cdot}70\mu$)	Green ($0{\cdot}5465\mu$)	Blue ($0{\cdot}436\mu$)
·400	·018	− ·006	·988
·410	·016	− ·006	·990
·420	·013	− ·005	·992
·430	·007	− ·002	·995
·440	− ·008	·004	1·004
·450	− ·035	·016	1·019
·460	− ·075	·041	1·034
·470	− ·144	·101	1·043
·480	− ·304	·246	1·058
·490	− ·580	·576	1·004
·500	− 1·004	1·229	·775
·510	− 1·142	1·725	·417
·520	− ·859	1·700	·159
·530	− ·502	1·453	·049
·540	− ·162	1·154	·008
·550	·079	·923	− ·002
·560	·302	·706	− ·008
·570	·489	·516	− ·005
·580	·642	·362	− ·004
·590	·763	·238	− ·001
·600	·846	·155	− ·001
·610	·902	·098	− ·001
·620	·939	·062	− ·001
·630	·966	·035	− ·001
·640	·982	·019	− ·001
·650	·990	·010	·000
·660	·994	·006	—
·670	·996	·004	—
·680	·997	·003	—
·690	·999	·001	—
·700	1·000	·000	—
White (4800° K.)	·333	·333	·333
Relative luminosities of primaries	23·1	100·0	1·08

I have given above, as suggested by Mr Guild, a table of the trichromatic coefficients re-calculated relative to the N.P.L. primaries. I have also given the relative luminosities of the primaries in this system. These were calculated by transformation from the values found for the other primaries. As the derivation of the mixture curves is then merely straightforward arithmetic, the data I have given will be sufficient for comparison with the N.P.L. results. I have not given a table of the complete mixture data as I had no complete set of figures available, and the work of completing the calculations and checking them was not possible in the time available.

In conclusion, may I express my great appreciation for the thoroughness with which Mr Guild has considered it worth while to criticise my papers. I consider I have been very fortunate to have had them subjected to such a close scrutiny by him.

THE PURPOSE AND DESIGN OF THE NEW EQUIPMENT AT THE ROYAL OBSERVATORY, EDINBURGH

By Prof. R. A. SAMPSON, D.Sc., F.R.S.

MS. received, 13th March, 1930. Read and discussed, 13th March, 1930.

ABSTRACT. The author deals with the reasons which determined the form of the telescope—a Cassegrain reflector of 36 inches aperture and 54 feet focal length, serving a spectrograph of one, two or three prisms—and indicates the problems to which it is intended to apply it. These are, generally, the intensity of stellar light for different parts of the spectrum. It is pointed out that even an empiric treatment of this question led Adams to a method that had doubled our knowledge of stellar distances. A theoretical treatment, comprising a discussion of the behaviour of the photographic plate, led to fixing the temperature sequence. A slit spectrograph is required in order to deal with the lines. The state of the lines, combined with that of the continuous spectrum, conveys all the information that reaches us of the star's constitution and atmosphere. Subsidiary but highly interesting questions are those of selective absorption of light by the atmosphere of the earth. Behind these are the theoretical and laboratory investigations of the relation between intensity of light and the density of silver deposit on the photographic plate. The whole presents an attractive field.

Astronomy is dependent upon Optics to such a degree that the astronomer hardly thinks of his task apart from its optical aids. But one may recall that the dependence of astronomy on optics, like its dependence on mathematics, is of that fertilising kind that states problems for solution and produces examples of their working, that could not otherwise be thought or done. So the dependence is mutual, they help one another, and if I succeed in conveying my ideas to-night, you will see that we are now in face of another step in the same round.

When I took up my duties at Edinburgh nineteen years ago, I remember Sir David Gill advising me "Don't go in for a big telescope, or people will expect you to make some discovery with it." It was good advice. The need for some development was pretty clear. All our telescopes dated from the seventies or earlier. But the remedy was not so crude as buying a big telescope from a maker and making discoveries with it. I turned first and developed the excellent system of clocks we now have at Edinburgh, at that time a much neglected field. There are many unsolved points of interest still about it. But it is only ancillary to Astronomy and it is certainly not Optics, so I pass it by. It was evident that at some time or other I must choose new telescopes.

In making a choice I found a good many things I could reject. Astronomical problems are not soon worked out, and it was requisite to find instruments that

suited not only my own tastes, but left a good practicable field for a successor. Parallax was one of the questions that offered. It is almost inexhaustible. But on the other hand it has been well organised, chiefly under Schlesinger's lead. Its technique has been reduced nearly to routine. And it is usually done with a long focus refractor. Now I consider a refractor, in the larger sizes, as almost an obsolete instrument. You have to provide two discs of matched glass, uniform and flawless, and figure four surfaces. This alone enhances the proportionate cost immensely. And the result is far from perfect. Achromatism is a mere approximation. Light is lost at each of the four surfaces and by transmission through the glass. Local differences of refractive index in the glass force on the maker the delicate task of final correction by local figuring. In the small sizes this can be done with certainty by the help of the interferometer, but not in large instruments. One solid advantage remains, if the refractor is to be used photographically—the four curvatures can be distributed so as to correct the field for coma. But coma does not matter if we are working at the centre of the field, as we do visually for double stars, or when we use a spectroscope. And in the Cassegrain form of reflector it is not very pronounced.

A large refractor almost demands the use of a rising floor, or some equivalent device. In this matter however the Newtonian reflector is under the same objection of requiring costly adjuncts.

A refractor with its cast centre piece, and double cone ends, both closed, is almost ideally stiff, and would seem for that reason better adapted to long exposures. But successful long exposures at Mount Wilson and elsewhere, some extending in duration to more than one whole night, show that if the reflector tube is carefully designed, it is in no way inferior. The same is true of the mounting and clock drive. Given equally accurate work the performance is equal. I decided then on the Reflector.

The best known use of the Reflector has been to give us direct pictures of the sky—the moon, clusters and nebulae, some of them truly marvellous, opening into a world previously unknown. But this kind of work is better done in the most favoured skies. At Edinburgh we have to reckon with very unstable weather, some beautiful spells indeed but of uncertain duration. Besides at its very best a direct picture of any object is less than we now know how to get. Compared to a spectrogram with its analysis of the light, a direct photograph of a star is as though we wrote a story with each letter on top of the last, when it was open to us to spread them out intelligibly. Of course you cannot spread without loss of intensity, and for a slit spectrograph, without great loss, thereby restricting your reach. But it appears to me that the gain in significance is immeasurable. The one registers merely existence and place, the other attempts to unfold the whole story which is contained in the light that, to us, *is* the star.

This makes the telescope, with all its elaborate perfections, an accessory serving the spectrograph, and therefore the latter determines its design. In particular, to secure purity in the spectra the collimator should be as long in focus as possible. Hence we must have a long focus telescope serving it, that is, the Cassegrain form,

with the great mirror parabolic and the second mirror hyperbolic. Such a telescope can be converted to the Newtonian form by changing the hyperbolic mirror for a plane one, but I am no believer in the universal instrument. Dr Plaskett, of the Dominion Observatory, Vancouver, whose designs for the 73-inch constitute, as I think, a landmark for future workers, and whom I have in general followed closely, has managed this problem, much more difficult in his case. But I feel there is enough without it. Both the money available, and the man power at the Observatory will go further, if spent upon the restricted instrument. This relates only to the great complication of plans involved in using the principal focus. The spectrograph itself is of the multiple type devised by Dr Plaskett, and both direct vision and direct photography of the stellar fields can be obtained at once by the insertion of a viewing eye-piece or a camera, at the Cassegrain focus.

All this will be better realised from the descriptions that follow: otherwise it is little more than a string of generalities. I now come to the more interesting matter of what I suppose that I shall do with the beautiful and convenient instrument you will hear described. It is simply this, an examination of the intensity of star light as it varies over the spectrum. You seldom get anything really new in astronomy, and this is not new. Not to pause at modern workers, Ptolemy recorded the magnitudes of stars and the colours of some of them. Estimates of colour, crude as they may be, have been shown by Hertzsprung to carry you very far. There has been some very good work in the field, but extraordinarily little of it when you consider that it comprises both astronomical questions of the radiating layers of the star and their physical state, and physical questions of emission and absorption under circumstances we cannot imitate on the earth, *besides* secondary matters like atmospheric absorption that are in truth mere nuisances, and only want eliminating, like atmospheric refraction, but have not been nearly so much studied.

There is nothing very new in these considerations. What I do think new is the Time of Day—I think we have come to a time when we can do something about it. In other words physics has already developed its resources until the astronomer can begin to put his material upon a scientific, that is, a significant, basis.

One has to make a choice, or rather two choices, one in the method of receiving the radiations, and the second in measuring what is received. For some years back I have studied these questions. A 6-inch photo-visual of 9 feet focal length, with an objective prism, was available. The spectra were recorded on panchromatic photographic plates of various makes, and the silver deposit measured with a photoelectric photometer, made in the Observatory, of Koch's pattern. The results were very distinctive. Not only the spectral lines characterising the different stellar types are apparent, but also the changing intensity from blue to red, superposed it is true upon the characteristic sensitivity of the emulsion used. Much else appears when they are measured. Thus it is the practice to begin and end each plate with a spectrum of Polaris, to serve as a standard for the others. Comparing the last and the first spectra of each plate, a small but unmistakable increase in the blue-transparency of the atmosphere in the course of the two or three hours of work is manifest. Of course there are inequalities, sometimes wild inequalities. But

these belong to the data. My conclusion from this work is that the method of reception and measurement wants little improvement, merely adaptation to what is of most interest, as by using an ortho-plate in place of a panchromatic, or so on, and that, given a satisfactory theory inferring from the measured photogram, the intensity of the light that produces the silver deposit, one is in a position to interpret significantly all the information the star light contains.

This is the essential theoretical problem, to relate the measure of the record, which is quite definite for each wave-length, with the intensity for that wave-length of the acting light. It seems to me impossible to overstate the interest of this problem. Even an empiric treatment which has no pretention to being a solution carries very far. For example, by treating very narrow bands of the spectrum, and obtaining empiric formulae connecting absolute magnitudes with the relative intensities of a few lines. Adams and his coadjutors at Mount Wilson have more than doubled our knowledge of stellar distances. But empiric treatment is merely a makeshift and its successes only a foretaste of what is in store. It remains, pending its supersession, which is bound to come. I have attempted a theoretical treatment, but as indicated above, I have so far only been able to deal with a single problem—the distribution of intensity in the continuous spectrum. Even that is sufficiently complicated. There is varying atmospheric absorption. There is instrumental absorption. There is for each special emulsion employed a determination of its behaviour under measured intensities of light. In this work I have been most ably helped by Dr E. A. Baker. But it would be no surprise to me or to anyone else to see the treatment I have given superseded in detail. I consider however that it *is* a fair facing of the facts, and that the conclusions it indicates are reliable. And the conclusion is, briefly, that we learn the temperatures of the stars, which follow closely the well-known and well-defined spectral sequence. You may imagine that we have known this fact for some considerable time. But at so recent a period as 1922 when I began this work there were great uncertainties in the determinations, amounting in some cases to a complete inversion of the spectral order.

I do not wish to make any claim as a pioneer. Apart from astronomy, everyone is well aware that estimates of intensity of lights and of their colour content are continual problems of lighting engineers. There are a great many difficulties in the work, with which I am not well acquainted—among others that of finding an absolute standard. The treatment is usually empiric, and in any case it is a comparison of light with light. If however we start with a light record and infer a temperature, we have shown that a real physical equation is soluble.

The prismatic camera is a very restricted form of stellar spectrograph. It works without a slit, so that though the lines are different in appearance from one another none of them is narrower than the tremor disc. Further it has not been found possible to use any comparison spectrum from a terrestrial source. To remedy these two faults you have the whole elaboration of the new telescope and spectrograph. It may seem that the gain is not proportionate. But my point is that we can now do, in quality, anything that *can* be done. I have no intention or wish to say what it will amount to. I will only say that though the telescope is moderate in

size as befits the atmosphere, and staff, and resources at Edinburgh, it is otherwise in no way inferior to the best.

Yet I would like to make clear that there is a field of straightforward work that is of sufficient interest and extent for anyone. Consider atmospheric absorption. For intensity work it occupies exactly the same place that atmospheric refraction occupied when astronomers were chiefly interested in finding positions. The mere literature, both theory and observation, of atmospheric refraction is immense, far more than one generation or one observatory could contribute. Yet the parallel question of atmospheric absorption, which may contain fruitful inferences as to the varying constitution of the earth's atmosphere, has been treated hitherto in the most summary fashion.

Well, that is useful, and only an inexperienced person would call it dull. Then there is the fuller examination of the relation of intensity of light to photographic deposit, and all the physical problems to which stellar spectrograms lead. But this is essentially laboratory work, suitable for the summer and when the weather is bad.

But if you want a really adventurous field of astronomy you have the intensity of spectral lines. There almost everything is unknown and theory itself somewhat tentative. At the present moment I speak for the observer, who has to use a telescope. The observer and the theorist may put on the same pair of boots, but they are different people. The observer tells the theorist what results he has to get, and if he is clever enough, he gets them. If it is ever the other way round, it is so rare as to be a brilliant achievement. Now the innumerable lines that stellar spectra reveal are quite unknown in measured intensity. They offer themselves in problems of all degrees of complexity, from the hydrogen series of the *A* stars onwards. The relations quite certainly tell the story of the state of the stellar atmospheres, using that word loosely. When we begin we may be a little misdirected in what we do, but that is not likely to endure for long. In fact nothing done systematically need be wasted, for it is sure to require to be measured, to permit advance beyond it. Personally I have no doubt, from the quality of the men that are working on the theoretical side, that they will disclose some principle that will serve as efficiently in the matter of line intensities as Doppler's principle has served for line positions. It would take too long to enumerate all that Doppler's principle has been made to yield in astronomical knowledge, but it is worth remembering that it entered first as a blunder. What I hope to see is, right or wrong, something as serviceable for intensities of lines. If it appears, half the observatories in the world will soon be working at it.

It is a good rule not to boast when you are putting on your armour. It is also a sufficient rule, for that is the only time you are likely to boast. I think the field a promising one, but I have no idea of boasting about it as though I discovered it or owned it. What would please me best would be that other people should come in and work at it too.

DISCUSSION

Mr W. B. Coutts: I have listened with great interest to Professor Sampson's account of the considerations which led to the design of the new equipment for the Royal Observatory at Edinburgh, and of the work for which he proposes to use it. The beautiful air photograph of the Observatory which was projected on the screen recalls to me many happy and profitable evenings spent there as one of his students. The site of this Observatory is a good one, and fortunately placed, in that the southern aspect is never likely to be marred by extensive building schemes which might interfere with observation owing to smoke. We must also note the foresight displayed by those responsible for the design of the buildings some forty or fifty years ago in providing a dome which can house this new instrument. While the largest instruments will still be found on the other side of the Atlantic where conditions for observation are most favourable, we must all feel glad that a really large, powerful and up-to-date reflector is being provided to further astronomical research in Britain.

Professor Sampson is to be congratulated on the result of his endeavours to obtain equipment suitable both for his projected researches and to the resources of the Observatory. The combined efforts of Professor Sampson, Messrs Sir Howard Grubb, Parsons & Co. and Messrs Adam Hilger, Ltd. have resulted in the design and production of a beautiful instrument which we are proud to recognise as a brilliant achievement of British Science and Industry. I am sure we all wish Professor Sampson every success with his new equipment. If anything, he has been too modest in describing the part he has played. The instrument will be in safe hands and we may be confident that its installation will be more than justified.

Mr M. Blood: I should like to ask Professor Sampson about one small point. In the slide showing the light intensity distribution in the spectra of different types of stars, there is a minimum in the green in every case. I presume this is a photographic and not a stellar effect.

Mr J. Guild: It is impossible without having had an opportunity of studying the diagrams at leisure to form an opinion of the merits of the design of the new telescope, as it is generally in minute points of detail rather than in the broad principles of design in which the potentialities of success or failure to give the hoped-for excellence of behaviour are to be looked for. One could not, however, fail to be struck, when listening to Professor Sampson's interesting talk and the subsequent descriptions of the apparatus, with the extent to which there has been co-operation between the ultimate users of the equipment and the manufacturers. This is the best insurance which can be made against the possibility of the finished equipment failing to come up to expectations. It is a course which could profitably be followed more frequently than is customary in the design of instruments of all kinds; but it is particularly necessary in a case like the present, where on account of the great cost of the equipment, it must, when once installed, serve for a very long time before it can be replaced or seriously modified.

The only point on which I would offer a suggestion is with regard to the spectrograph. I should have thought that for astronomical work, involving as it does long exposures with the consequent necessity of guarding against temperature effects in the spectrograph, an autocollimating system of the Littrow type would be preferable to the elbow type of spectrograph employed, because of the greater ease with which the former system can be rendered sensibly immune from the effects of varying temperatures.

Dr D. S. Perfect: I should like to ask Professor Sampson what extent of spectral range it is hoped to study.

Mr F. Twyman: I should like to join with other speakers in expressing my gratification that the British Isles are at length provided with a really large telescope of modern construction and high quality.

I think that the Optical Society should particularly congratulate itself that the pages of its journal will contain a record of this most important equipment.

I have been most interested to learn from Professor Sampson's paper of the important and interesting purposes in view, and am relieved to learn that they are of a nature to be fulfilled in our climate.

Professor R. A. Sampson (communicated): In reply to Mr Blood's question, the spectrograms were taken upon panchromatic plates which respond strongly to the red as well as the blue but are relatively weak in the green. This, as he suggests, is purely a photographic feature and must be eliminated before any physical conclusions are drawn.

As to the range of observations it is proposed to cover, it will be moderate, in correspondence with the whole conception of the instrument; but if I can go as far as the sixth magnitude, that will leave an ample field of work.

A DESCRIPTION OF THE THREE PRISM SPECTROGRAPH FOR THE ROYAL OBSERVATORY, EDINBURGH

By J. H. DOWELL, F.R.P.S.

(Designs Department, Messrs Adam Hilger, Ltd.)

Described, 13th March, 1930.

The Mechanical Construction

The design of the spectrograph follows closely that of the Dominion Observatory, Vancouver, with such improvements as experience has shown desirable.

The diagram shows a general view of the spectrograph. The whole instrument is attached to the telescope by the box-shaped support *A* which is bolted on to a worm wheel. The spectrograph is mounted on a shaft *B* carried by the box support *A*, and restrained from rotating on the shaft by a pair of opposing pins *C*. With the exception of its location on the shaft and restraint by the opposing pins, the spectrograph body is entirely free and does not make contact with the support at any other point. Adjustment for setting the spectrograph in line with the telescope axis is provided in all directions by mounting the spectrograph body on a spherical bearing *D* at one end of the shaft, at the other end are three adjusting screws enabling the body to be tilted. Cross motion is effected by the screwed rings *G* on the shaft bearings. Note the screwed rings are both inside and outside each bearing so that both limbs of the support take their proper share of the weight no matter in what position the spectrograph may be. The final adjustment about the axis of the shaft is controlled by the opposing pins *C* which are provided with adjusting screws for this purpose. It will be noted that this method of restraint allows for the free expansion in all directions without the risk of imposing strain on the spectrograph body.

The spectrograph body *H* is a one-piece casting in aluminium. The point of greatest importance here is to provide a mount for the optical components having the greatest possible strength combined with the minimum weight. The importance of a ridged mechanical structure will be appreciated when it is realised that a deflection of $\frac{1}{1000}$ inch along the length of the plate (using the medium length camera) corresponds to an error in radial velocity amounting to 40 mils/sec.

Dr J. S. Plaskett has pointed out that the chief source of weakness in a spectrograph body of this type is due to the large opening usually provided for access to the prisms, and this we confirmed from tests made on a model.

This defect was overcome by arranging for two strong webs across the opening and by a system of flanges designed to prevent distortion of the base. Tests made on a model so constructed showed a surprising increase in strength with very little increase in weight.

The collimator consists of a steel tube *J* securely mounted in the spectrograph body. The upper end which carries the slit draw tube has six radial saw cuts over which are a pair of clamping rings designed to grip the slit draw tube firmly when

it is in focus without risk of shake. Focussing of the slit is effected by rack and pinion motion.

The slit is similar in principle to the slit employed in the Dominion Observatory. One jaw is fixed and the other controlled by a micrometer reading to 0·001 inch. Both jaws are of stainless steel. The comparison spectra is introduced on both sides of the main spectra by a pair of prisms so mounted that the distance between them can be varied as required by the height of the main spectrum.

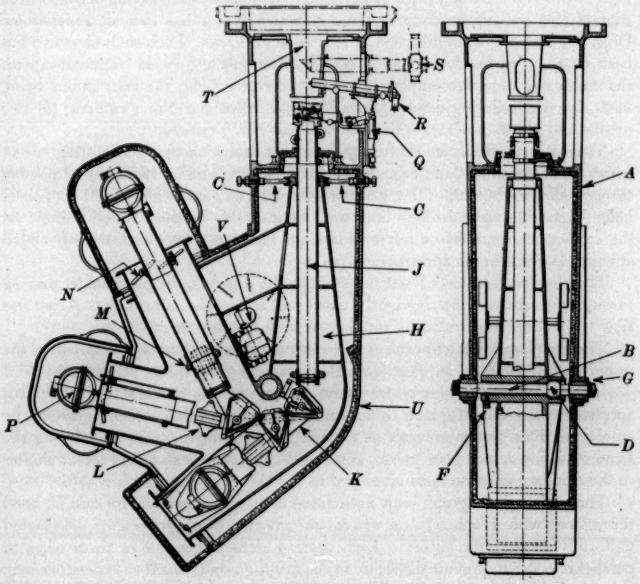

Fig. 1.

The prism system consists of three prisms so mounted that either one, two or three prisms in train can be used if necessary with any one of three available cameras. The prisms are made of a highly transmissive dense flint glass of refractive index μ_D of 1·623. They each have a refracting angle of 60° and increase in size from the first prism to the third in order to prevent loss of light in the case of more than one prism being used.

The prisms are mounted on minimum deviation gearing *K*, but contrary to usual custom the camera mounts are attached direct to the adjacent prism mount. For instance, if two prisms are used, the camera is attached direct to the mount of

the second prism. This was done in order to simplify the gearing, as it was felt that the small departure from minimum deviation between the last prism and the camera did not justify the additional complication. When set in position all parts can be securely clamped by bolts direct on to the spectrograph body so as to eliminate possibility of shake.

The three interchangeable cameras above referred to have aperture ratios as follows: No. 1 camera, $F/6$; No. 2 camera, $F/11{\cdot}1$; No. 3 camera, $F/15$. Objectives Nos. 1 and 2 are of a triple construction. Objective No. 1 having one cemented contact and one air separation, while objective No. 2 has two air separations. Objective No. 3 is a combination of two separate lenses. Each such objective has been designed expressly for use in this spectrograph to give, in conjunction with the collimator objective employed, a fully corrected field, the calculations being made for the following combinations: (*a*) one prism and No. 1 camera; (*b*) two prisms and No. 2 camera; (*c*) three prisms and No. 3 camera.

The cameras are located on the prism table extension by a long fitting one of which can be seen at *L*, and are secured at the prism end by two bolts *M* passing through slots in the wall of the spectrograph body, and at the plate end by a pair of bolts *N*, passing right through both walls of the body between which a frame on the camera is fitted. Thus not only are the cameras firmly secured but added strength is given to the spectrograph body.

The ring form cameras *P* will be noted on the drawing, the plate holder passing through the centre of the ring by the usual rack and pinion adjustment. A fast and slow tilt motion is provided by rotation of the inner ring member.

The arc *Q*, guiding telescope *R* and viewing telescope *S* are all mounted on the upper part of the main support, as is also a camera *T* for direct photography.

In addition to the above-mentioned optical systems of glass a single prism spectrograph system of quartz, interchangeable with the glass system, may also be employed. This system consists of a cornu prism of angle 66° 14′, producing the same deviation as one glass prism, and single collimator and camera lenses similar to the standard constructions employed in the Hilger Spectrograph E 316.

The entire spectrograph body is enclosed in an outer temperature case *U*, lined throughout with $\frac{1}{2}$ inch felt, on which are mounted heating elements distributed uniformly all over the surface. Each heating element consists of three wires in parallel in order to provide flexibility in the heating arrangement as experience may show desirable. The heating arrangement adopted for trial is divided in two parts, one consisting of two of the three heating elements arranged in parallel through which a hand controlled current is passed, and the other heating element controlled by temperature regulating apparatus.

The temperature control consists of a Cambridge Instrument Co.'s Wheatstone bridge regulator operating a relay, the apparatus is designed to maintain a temperature of $\pm$ 0·05° F. Circulation of the air is secured by an electric driven fan *V* rotating at slow speed.

The circulating air passes round the outside of the spectrograph body and is prevented from entering the interior by plates covering the unoccupied apertures for the camera and by plates fitting round the camera in use.

A DESCRIPTION OF THE 36-INCH APERTURE TELESCOPE FOR THE ROYAL OBSERVATORY, EDINBURGH

By C. YOUNG

(Messrs Sir Howard Grubb, Parsons & Co.)

Described, 13th March, 1930.

THIS Telescope, the largest Reflector in Great Britain, has been designed and constructed by Messrs Sir Howard Grubb, Parsons & Co., at the Optical Works, Newcastle-on-Tyne, in collaboration with Professor R. A. Sampson, F.R.S., the Director of the Observatory. It is of the Cassegrain form and is to be used chiefly for spectrographic observations, but is also adaptable for other purposes.

Optical System

The optical system consists of two parts:

(*a*) The great, or parabolic, mirror, of 37 inches diameter by 6 inches thick, with a central hole 3½ inches diameter, and focal length 15 feet ($F/5$).

(*b*) The secondary, or Cassegrain mirror of hyperbolic section, 10 inches diameter. This is used in conjunction with the main mirror and is designed to give an equivalent focal length of 54 feet ($F/18$), the rays passing through the aperture in the great mirror and being brought to focus at a point about 22 inches behind its front surface.

Telescope Mounting. General Arrangement

The equatorial mounting is of the usual crosshead type, in which the declination axis is placed above the upper bearing of the polar axis.

Main Stand

The main stand is built up of three cast iron castings, the lower part being of box form, about 4 feet 9 inches long by 3 feet wide by 2 feet 6 inches high, and carries the upper and lower bearings for the polar axis. The gear plate and control are mounted in the upper part of the stand, the driving clock and right ascension quick motion gear being fixed in the lower part. The apertures in the stand are closed by removable plate glass windows in teak frames.

Polar Axis

This is made in two parts, the upper portion consisting of a tapered iron casting, the lower part being a steel forging rigidly attached to the upper part. It is inclined at an angle of 57° to the horizontal to suit the latitude of Edinburgh, and is mounted in self-aligning ball bearings, with a ball thrust at the lower end. During manufacture the whole axis was very carefully turned, the final truing up of the pivots, and the fitting for the driving circle, being done in a vertical lathe on a dead centre at the bottom and a steady bearing at the top.

Driving Wheel

The driving wheel is of cast iron, mounted on ball bearings on the polar axis, so that it can turn freely on the latter. The rim on which the teeth are cut is of bronze, there being 1080 teeth with a pitch diameter of 54·137 inches. The teeth were set off from a very accurate master circle graduated on silver, mounted concentrically upon it, each line on the master circle being brought into coincidence with the graticule in a reading microscope, for cutting each tooth. A second microscope of the master circle was used as a check.

Right Ascension Clamping Gear

This is operated by means of a $\frac{1}{10}$ H.P. motor. A worm wheel, driven by the motor, carries a set of contacts so arranged that one action of a two-way switch controlling the motor allows the worm wheel to make a half revolution. A second action of the switch causes the worm wheel to make a second half revolution.

The spindle of the worm wheel carries an adjustable crank which operates three nearly-radial rods carrying wedge-shaped pieces at their outer ends. When the crank is at one end of its stroke these three rods are each forced equally against a pair of arms which engage with an internal **V** ring mounted on the driving circle and clamp it rigidly to the quick motion wheel.

Crosshead and Declination Axis

The crosshead, which is of cast iron, is rigidly bolted at right angles to the flange formed on the upper end of the polar axis.

The declination axis, which is of forged steel, is mounted in the crosshead in two radial ball bearings and a double thrust bearing. The inner end of the axis is formed into a flange, 23 inches diameter, to which the centre piece of the tube is bolted. At the outer end of the crosshead is mounted the motor-driven quick motion gear for setting in declination.

Right Ascension Quick Motion Gear

This is similar to the declination quick motion gear, and is mounted on the lower part of the stand and operated by a $\frac{1}{4}$ H.P. reversible motor. Both this and the declination gear are fitted with friction governors, which limit the speed of rotation

of the axis to four revolutions per minute. The motors are automatically disconnected from the gears when not in use.

Right Ascension Circles

An R.A. circle, 18 inches diameter, graduated on silver and read by a micrometer microscope, is mounted on the toe of the polar axis. A siderial circle, 42 inches diameter, roughly graduated and figured, is mounted on a boss formed on the driving circle and can be set by hand to siderial time.

Declination Circles

These are mounted on the inner end of the crosshead. The fine circle, 30 inches diameter, graduated on silver, is read by means of two micrometer readers attached to the tube. The rough circle, 36 inches diameter, is graduated to single degrees.

Declination Clamp and Slow Motion

This is fitted on to a V ring attached to the inner end of the crosshead. Clamping is effected by means of either of two hand wheels fitted at opposite sides of the lower part of the tube. The outer end of the clamp arm carries a nut engaging with a fine thread screw mounted in a bracket attached to the side of the tube. This screw carries a worm wheel engaging with a worm connected to the motor-driven slow motion gear. Two speeds are provided, one for guiding, giving a movement of the tube of 15 seconds of arc in one minute of time (or one complete revolution of the axis in 60 days), the other speed, for setting, being about 30 times faster.

Tube

The tube consists of three parts:

(*a*) The centre cast iron casting, bolted to the end of the declination axis.

(*b*) The upper part, of lattice construction.

(*c*) The main mirror cell bolted to the lower flange of part (*a*).

The main mirror rests on nine circular pads, 4 inches diameter, mounted on three triangular supports, so disposed as to give an equal pressure on nine portions of equal areas of the back of the mirror. Nine weighted levers are disposed round the cell, mounted on universal joints and engaging with eyes mounted on a flexible band which is clamped round the periphery of the mirror. These levers gradually take its weight as the tube is inclined towards a horizontal position.

A roller blind is fitted in front of the mirror to protect it when not in use.

Guiding Telescope

A guiding telescope of 7 inches aperture, fitted with a two-lens apochromatic objective of 12 feet 7 inches focus, is fixed alongside the main tube. The eye-piece is mounted on cross-slides with quick and slow motions, allowing 3 inches travel

in the two directions, the position scales being electrically illuminated. The spider lines in the eye-piece can be either bright against a dark field, or dark against a bright field as desired.

Three eye-pieces are provided giving magnifications of 200, 400 and 600.

Finders

Two are provided:

(*a*) A telescope of 3 inches aperture by about 3 feet focal length with a magnification of 18 diameters.

(*b*) A prism monocular, magnifying nine times, with objective 35 mm. diameter.

Driving Clock and Gear Plate

The driving clock is housed in the lower part of the stand, and mounted direct on the pier on which the telescope is fixed. It is driven by a weight which is automatically wound up by $\frac{1}{20}$ H.P. motor. The speed of the motor is controlled by means of a regulating resistance operated through a lever linked to the driving weight. In practice it is found that the position of the weight does not vary more than about $\frac{1}{8}$ inch.

The friction governor makes 130 R.P.M. and is coupled by a vertical shaft to the gear plate and driving screw.

The gear plate is fitted with a controlling mechanism which receives an impulse every second from one of the standard clocks in the observatory; any errors in speed of the driving shaft being automatically corrected by means of differential gears.

Quick-slow and slow-slow motions, actuated by a hand commutator for setting and guiding, are also provided.

PHOTO-ELECTRIC CELLS AND THEIR APPLICATIONS

A DISCUSSION AT A JOINT MEETING OF THE PHYSICAL AND OPTICAL SOCIETIES, JUNE 4 & 5, 1930

The following papers were presented:

THE EARLY HISTORY OF PHOTO-ELECTRIC AND SELENIUM CELLS. By Professor H. S. Allen, M.A., D.SC., F.R.S.

A brief account is given of the discovery of photo-electricity and of the laws obeyed in the emission of photo-electrons. The early attempts to employ photo-electric cells in photometry are described and the main types of cell are indicated. Two actions of light on selenium are described—(1) the change in resistance discovered by Willoughby Smith and May, (2) the production of an electromotive force when selenium is used as an electrode in an electrolytic cell.

A THEORY OF SELECTIVE PHOTO-ELECTRIC EMISSION (with special reference to thin films of caesium on silver). By N. R. Campbell.

An attempt is made to apply to photo-electric emission the conception of a transmission coefficient developed by Nordheim and Fowler in their application of wave-mechanics to thermionic emission. It appears that, if subsidiary assumptions of some plausibility are made, a satisfactory qualitative account can be given of normal photo-electric emission that involves no ideas that are not now firmly established.

The problem of selective emission is more difficult; it appears to require that the surface should transmit selectively electrons within a narrow range of velocity. In order to ascertain whether such a theory would be tenable, the problem is attacked in two halves. First, an attempt is made to discover what is common to all selectively emitting surfaces. It appears that the presence of an electronegative element is a universal feature; and it is suggested, on thermionic analogy, that this element forms a cement uniting a more electropositive layer (probably monatomic) on the outside to a massive but less electropositive metal on the inside. Support for this view is found in an examination of the formation of the cathodes of caesium on oxidised silver that have been described by Koller; this formation is described in detail.

Second, it is asked what surfaces might be expected to transmit selectively. A suggestion given by recent work of Fowler and Wilson, which is being developed by Fowler in a separate paper, indicates that, if the distribution of potential through the surface layer of the cathode were such as to form a potential "valley" between two potential "peaks," selective transmission would occur when the velocity of the electrons was such that the waves associated with them were capable of forming standing waves between the sides of the valley. A re-examination of the facts in the light of this suggestion leaves it possible that the constitution of selectively emitting cathodes may indeed satisfy this condition.

THE STANDARDISATION OF PHOTO-ELECTRIC CELLS. By N. R. Campbell.

The photo-electric cells offered for sale by different makers are so different and so differently described that some standardisation is urgently necessary. The type of gas-filled cell that is now widely used for the reproduction of talking films and similar purposes ought to be standardised in respect of size, arrangement of terminals and running voltage. Other

types of cells should not be standardised at present in this sense. But standard methods of describing the performance of all cells are desirable. Proposals are made for standard descriptions of the emission and of the characteristic of gas-filled cells.

THE MANUFACTURE, PROPERTIES, AND USE OF SODIUM PHOTO-ELECTRIC CELLS. By Dr P. Selényi.

This paper contains the results of the photo-electric investigations carried out in recent years by the staff of the Tungsram research laboratories. After a brief description of the manufacture of ordinary sodium-cathode photo-electric cells by glass-electrolysis (C. R. Burt, L. Márton and E. Rostás) the author describes his own experiments on these cells, especially the two different methods found by him for making sodium cathodes red-sensitive. The first method, in which the sodium surface is covered with a very thin layer of nickel, results in high sensitivity lasting for a few hours only. The cells made by the second method, i.e. by introducing oxygen into the bulb by the electrolysis of the glass wall, keep the same valuable properties (red-sensitivity and high overall sensitivity) and last a very long time. The following sections of the paper are devoted to a discussion of the use of photo-electric cells for different purposes. The employment of alternating voltage for the measurement of photo-electric currents is dealt with, a few new methods for controlling electromagnetic relays by means of photo-electric cells are described, and the use of photo-electric cells for photometric measurements is discussed.

THE MANUFACTURE AND USE OF THE THIN-FILM CAESIUM CELL FOR SOUND REPRODUCTION. By L. J. Davies, B.A., and H. R. Ruff, B.SC.

This paper describes briefly the development and production of the "Mazda" thin-film caesium cell. Curves showing the variation of sensitivity with wave-length of light are given, and these, combined with other curves showing the energy radiation of lamps and the energy transmission of films, demonstrate the suitability of the caesium cell for sound reproduction.

BARIUM PHOTO-ELECTRIC CELLS. By Theodore W. Case.

Photo-electric action was discovered in Western Electric audion bulbs and the active material determined to be barium and strontium sub-oxides. This is in line with work done on other photo-electric substances such as thallium oxy-sulphide and silver sub-oxide.

The first barium cells were made with a platinum filament containing 10 per cent. rhodium. This filament was coated first with calcium oxide and then with barium oxide, and a nickel plate was used as cathode, being subsequently replaced by chemically deposited silver. Under high vacuum conditions the oxide coating on the filament is activated by an alternating current field and active material is evaporated from filament to plate.

Gas-filled cells are made by forming barium hydride by arc discharge in the cell. The correct pressure of hydrogen is determined by galvanometer readings. Four quartz gas-filled cells were made, using a similar method. Stable barium cells could not be made using lead glass. This is probably due to the fact that lead is freed by the filament activation process and has a deleterious effect.

The barium high vacuum cell is successful for daylight measurement. A high transmission yellow filter was developed to correct the response of the cell to correspond to that of the human eye. Also a shield was worked out so that the cell will follow the cosine law for the angle of incidence of impinging light. The barium hydrogen-filled cell is quite sensitive, giving approximately 98 microamperes per lumen of light flux. These gas-filled cells lose their sensitivity in the dark but regain their original action in 15 secs. upon exposure to light. There are as yet practically no data regarding the quartz cell.

Curves are given showing the effect of applied voltage on a high vacuum cell, the spectral sensitivity of the barium high vacuum cell with and without the high transmission yellow filter, the characteristics of this cell with and without the shield, and the spectral sensitivity of the hydrogen-filled cells in quartz and in glass. The spectroscopic analysis of the active surface of a barium cell in G 702-P glass is also shown.

THE MANUFACTURE OF PHOTO-ELECTRIC CELLS AND THEIR USE IN SOUND REPRODUCTION. By Donald H. Loughridge, PH.D.

Various classes of photo-electric cells are discussed as to their basic mode of operation and reasons for the fatigue commonly present in some types of cells. The method of manufacture of a common high vacuum cell, free from fatigue, is discussed at some length as well as the gas-filled adaptation of this same type. Problems associated with the utilisation of photo-electric cells in the talking motion picture field are mentioned.

PHOTO-ELECTRIC CELLS AND SOME APPLICATIONS. By Jakob Kunz.

In the cells described the anode consists of a ring with or without a cross of very fine wire, or in double sphere and double cylinder cells the outer glass is half-silvered and serves as anode. Recently gold-caesium cells have been constructed which show a fairly constant sensitiveness throughout the visible part of the spectrum. A new type of photo-electric valve is described.

Vacuum and gas-filled cells when properly constructed give a linear relation for light intensities varying from 1 to 100 units and in some cases from 1 to 10,000 units, i.e. to full sunlight. For very strong illumination, as, for instance, for sunlight, the cells can still give proportionality for certain, mostly low, voltages. For higher intensities than about 700 foot-candles at 85 volts the curve bends towards the abscissa, the current becoming approximately proportional to the logarithm of the illumination.

TIME-LAG IN GAS-FILLED PHOTO-ELECTRIC CELLS. By N. R. Campbell and L. G. Stoodley.

It has often been reported that the response of gas-filled photo-electric cells, that is to say, the ratio of the amplitude of the photo-electric current to the amplitude of a varying illumination, decreases when the frequency with which the illumination varies rises above a few thousand cycles a second. Until lately the evidence has not been entirely satisfactory, because the measurements have been made with amplifiers without due attention being paid to their characteristics. But recently quite definite evidence has been produced by Metcalf; part of his results are confirmed here by experiments arranged so as to eliminate the characteristics of the amplifier entirely.

Since the same effect is not found in vacuum cells, and since it increases with the voltage applied to gas-filled cells, it must be connected with the magnification of the primary photo-electric current through ionisation. The obvious theory that the process of ionisation takes a finite time, and therefore smooths out variations in the light, appears inconsistent with calculations of the time that the process ought to take. Further evidence is produced against that theory by the discovery that the "time-lag" is not closely connected with the geometrical form of the cell.

A COMPLETE ELECTROSTATIC METHOD FOR THE MEASUREMENT OF PHOTO-ELECTRIC CURRENTS. By Eric B. Moss.

The method is a null one and developed to suit the Lindemann electrometer. Improvements are incorporated which simplify both the electrical circuit and manipulation. By collecting all the auxiliary apparatus into a compact unit which is heated electrically,

insulation and other errors are eliminated. The method is absolute as the actual photo-electric current is measured and widely different intensities can be determined. Either gas-filled or vacuum cells may be used.

A Method of Comparing very Small Amounts of Light by Means of a Photo-Electric Cell and a Valve Amplifier. By G. M. B. Dobson, M.A., D.SC., F.R.S., and D. S. Perfect, M.A., D.PHIL., F.INST.P.

The paper describes a method of comparing the relative intensities of two beams of light, and of detecting or measuring a single extremely faint beam. By means of a rotating shutter the two beams are admitted alternately to a photo-electric cell. Any difference of intensity in the beams produces a ripple in the photo-electric current which is amplified by a low-frequency amplifier. The alternating current from the amplifier is rectified by a commutator attached to the shaft of the rotating shutter, and the rectified current is measured on a microammeter or galvanometer.

A Theoretical Investigation of the Use of a Photo-Electric Cell with a Valve Amplifier. By N. L. Yates-Fish, B.A.

A method is given of estimating the performance of a resistance-coupled amplifier at various frequencies. It is shown that a photo-electric cell illuminated by a modulated source of light is equivalent to a generator of high internal resistance, and the effect of the capacity and leakage of the first grid is then investigated. The fluctuations of the galvanometer are briefly discussed.

A Theoretical Study of the Amplification of Photo-Electric Currents by Means of Thermionic Valve Amplifiers. By H. A. Thomas, M.SC., A.M.I.E.E.

The paper presents a theoretical analysis of the photo-electric cell and thermionic amplifier combination when used for detecting small amounts of light. The current sensitivity is obtained together with the optimum conditions for operation. The results are applied to cases likely to arise in picture-telegraphy and television, and frequency-response characteristics are plotted for particular cases, illustrating the effects predicted from the theoretical analysis.

Distortion in the Amplification of Photo-Electric Currents and a Remedy. By Dr Heinrich Geffcken and Dr Hans Richter.

The effect of distortion in the amplification of photo-electric currents is dealt with, and a new type of cell is described which gives very much higher sensitivity under certain voltage conditions. The cause of the particular phenomenon which conduces to this result is discussed.

A Method of Measuring Small Angles. By D. S. Perfect, M.A., D.PHIL., F.INST.P.

The paper describes a method of measuring angles less than 15 seconds with a probable error of the order of 0·05 sec. Settings are made by causing an image of a fine slit to fall on the edge of a steel prism worked to razor-like sharpness. The prism divides the beam of light into two components, the relative intensity of which forms the criterion of the position of the image of the slit. The relative intensity is measured by allowing the component beams to fall in rapid succession on a photo-electric cell, the ripple in the current through which, due to any inequality of the intensities, is amplified by a low-frequency amplifier. The alternating current from the amplifier is rectified by a commutator, and the rectified

current, measured by a galvanometer, is taken as a measure of the relative intensity of the two components. Displacements of the beam of light which forms the image of the slit are measured by giving a compensatory displacement by means of a hollow prism, the internal air-pressure of which is varied and measured.

NOTES ON PHOTO-ELECTRIC PHOTOMETRY. By Clayton H. Sharp, PH.D.

An attempt is made to classify and describe briefly certain methods of photo-electric photometry which have come under the writer's observation and have proved their practical utility through extensive use in commercial laboratories over a period of some years. The methods of procedure are divided into three classes: Class 1, involving linearity of valve response and amount of amplification; Class 2, involving linearity of cell response alone; Class 3, involving linearity of neither cell nor amplifier. Problems connected with the measurement of the transmission of colour filters, work in the ultra-violet, colour response, and colour matching are discussed. The conclusion is reached that photo-electric methods of photometry are much superior to the older methods, at least in connection with the production and testing of incandescent lamps on a large scale.

THE PHOTO-ELECTRIC CELL AS A PRECISION INSTRUMENT IN PHOTOMETRY. By T. H. Harrison, B.SC., PH.D., A.INST.P.

The characteristics of photo-electric cells are discussed with reference to their application to photometry of high precision. Several faults which photo-electric cells still possess, such as dark current, variation of sensitivity with time of illumination, lack of proportionality between photo-electric current and illumination, unsuitable colour sensitivity, leakage of the photo-electric current, and unequal sensitivity over the cathode, are discussed and methods are indicated by which the effects of these can be completely eliminated.

Suggestions are given as to the features which should receive most attention in the design of photo-electric cells intended for photometric use.

ON THE PHOTO-ELECTRIC MEASUREMENT OF DAYLIGHT. By W. R. G. Atkins, SC.D., F.R.S., and H. H. Poole, SC.D.

For daylight photometry in most situations we have found sodium or potassium vacuum cells to be the most suitable, though their relative insensitivity to wave-lengths longer than about 5000 A.U. is a disadvantage. A new type of caesium vacuum cell, which is sensitive to the whole of the visible spectrum, has given very promising results. Gas-filled cells may be used if the light is very weak. Precautions must be taken, however, to eliminate the effects of possible changes of sensitivity during the measurements.

Owing to the wide variations that occur in the angular distribution of daylight it is desirable to mount the cell behind a diffusing surface. We have found a type of opal glass very suitable for this purpose.

Various methods of measuring the current have been used, sensitive portable galvanometers being the best where a steady support is available. For use at sea in a small vessel a potentiometer-valve-telephone method seems to be the most convenient, while for work in a small boat the flashing neon lamp may be used. Electro-chemical methods are convenient for finding the average illumination over a definite period; or a continuous record may be obtained by means of a thread recorder.

The pronounced blue-sensitivity of most cells presents certain difficulties in their standardisation. A method of standardising by means of a carbon arc is described.

A short account is given of some recent work with the new red-sensitive cell, illustrating its use to measure changes in the colour of daylight.

A Photo-Electric Integrating Photometer. By A. S. G. Hill, B.SC.

The paper describes an application of the photo-electric cell as a means of measuring the illumination from a Bennett integrating photometer, and illustrations of its use are given.

The Neon Discharge Tube Photometer. By J. H. J. Poole, SC.D., and H. H. Poole, SC.D.

A description is given of a form of photometer which uses the rate of flashing of a neon discharge tube, when shunted by a suitable capacity, to measure the current from a photo-electric cell. The general design and standardisation of the instrument are discussed, and curves illustrating its behaviour are given. Finally some practical trials with it for sub-aqueous light measurements are described.

The Photo-Electric Cell as an Essential Part of the Recording Micro-Photometer. By Peter Paul Koch.

Reference is made to the methods of photographic photometry, and the characteristics of the photo-electric cell which are of importance in its application as a light-sensitive detector to the measurement of photographic densities are described. It is shown that, with proper manipulation of the cell, the effects of lag, fatigue, and recuperation may in practice be ignored. Finally, reference is made to the special advantages of the compensation method, which makes the results obtained with the registering photometer independent of the intensity of the source used for illuminating the photo-electric cell.

Some Factors Affecting the Speed of the Koch Micro-Photometer. By E. A. Baker, D.SC., F.R.S.E.

The time taken by a photo-electric photometer of the Koch type to arrive within 1 per cent. of its equilibrium value is examined and an account given of the methods adopted to reduce this time in a practical case. The best results were obtained by using a "leak" cell with a small central cathode and by avoiding large windows or other insulating surfaces in the cells. In these ways the response time is readily reduced to half a second, but is not brought below a tenth of a second even with very high illuminations on the cells.

The Use of the Photo-Electric Cell in Spectrophotometry. By Dr K. S. Gibson.

The greatly increased use of colour in industry and the home makes it highly important that methods for the rapid and accurate analysis and specification of colours be available. The only complete method of analysis of colour stimuli and the most fundamental method of specification is the spectrophotometric method. Of the various methods of spectrophotometry available, that using the photo-electric cell can be made by far the most rapid and probably has the highest precision of any available. The advantages and limitations of the new photo-electric spectrophotometers are discussed, particularly the bearing of various factors on the accuracy of the results obtained by them. Previous uses of the photo-electric cell in spectrophotometry are briefly described.

Spectrophotometric Absorption Measurements. By D. S. Perfect, M.A., D.PHIL., F.INST.P.

The paper describes various methods of photo-electric spectrophotometry which have been developed, and discusses their relative merits, chiefly from the point of view of the detecting system. The methods dealt with are those depending on (*a*) the absence of change

in the deflection of a quick-period electrometer, (*b*) the absence of change in the deflection of a slow-period electrometer, (*c*) relative deflections in equal times, (*d*) relative times of equal deflections, (*e*) zero deflection where two cells are used in opposition, and (*f*) zero deflection where two beams are rapidly alternated, and the photo-electric current is amplified, rectified, and indicated by a galvanometer. Of these methods (*a*), (*b*), (*c*) and (*d*) are suitable for use with steady sources of radiation, (*a*) and (*e*) are suitable for moderately unsteady sources, and (*f*) is suitable for very unsteady sources. In connection with one of the methods special types of rotating sectors are described.

A Spectrophotometer for Measuring the Amount of Ozone in the Upper Atmosphere. By G. M. B. Dobson, M.A., D.SC., F.R.S.

The instrument consists essentially of a double spectrograph in combination with a photo-electric cell and a shutter and commutator. Two narrow bands in the sun's ultra-violet spectrum are isolated, their wave-lengths being chosen so that one of them is strongly absorbed by ozone and the other is but little absorbed. When the relative intensity of these bands is measured by the method described in another paper it is possible to calculate the amount of ozone through which the light has passed.

The Use of Photo-Electric Cells in Biological Work. By V. E. Shelford.

As the flat surfaces commonly used to receive solar radiation are unlike the convex bodies of plants and animals, cells with sensitive surfaces in the form of spheres, cylinders, convex and concave hemispheres were tried. Cell form is best tested by continuous recording of sunlight with a potentiometer recorder.

The response of a double cylinder cell rose to 70 per cent. of its maximum within 30 min. after sunrise. The concave cell behaved more nearly like the double cylinder one. The apparent intensity rose to 80 per cent. of the maximum in 2½ hours and a little later increased slightly to the maximum as the cylindrical cell did. Response increases very rapidly with the increase in surface exposed.

A double sphere cell followed the normal curve of intensity as calculated from air mass data for the wave-lengths to which it is most sensitive except that it showed an increase for a time when the sun's elevation was about 45°. The cell was mounted about 30 ft. above the ground and this increase was attributed to reflection from below.

While much work remains to be done, our most successful cell was a collapsed sphere cell with convex hemispherical sensitive surface. Its curve for the forenoon was most nearly comparable with the calculated intensities for the sun alone and showed a direct proportionality between intensity and current. A new design for this cell with accessories has been described elsewhere.

Ray filters should ordinarily be of glass. Plates of spherical curvature can be made from special glasses by the Corning Glass Company, Corning, N.Y., and ground to uniform thickness. Measuring circuits should be simple, such as unipivot instruments of several ranges so that the voltage of the batteries can be read on the same instrument as the cell current. The use of direct-reading instruments reduces the number of connections to absorb moisture.

The terrestrial and shallow water outfit may include a vacuum cell to be used as a standard for the gas-filled cells. For use under water, clear vaseline was found to afford perfect insulation. Surface absorption varies greatly with cell form and screen colour. Peculiar optical properties of water with its suspended matter and transparency to different colours have been noted.

The information which should be available to purchasers of photo-electric cells is discussed, and a list of American makers of cells and accessories is given.

PHOTO-ELECTRIC PHOTOMETRY IN RELATION TO PHOTOTHERAPY. By Harry D. Griffith, B.A.

A fully successful system for photometry of therapeutic lamps requires more knowledge of the physiological actions of light than is now available, but provisional solutions can be found. Consideration of the relation of response to wave-length for equal energies in a number of relevant cases, such as the action of light on proteins or on human skin, shows that the long-wave limit of sensitivity of the photometer should be about 313 mμ, but the best form for the response curve for shorter waves is difficult to choose. The selection of the erythema curve as found by Hausser and Vahle in 1921 as the sole basis is arbitrary and misleading if the re-determination of the curve (1928) is ignored. The author suggests a flat characteristic from 313 mμ to 250 mμ for the response curve of the photometer as the best compromise. Cadmium photo-electric cells are widely used because of the appropriate position of the threshold wave-length, either with bare quartz windows or with a screen of uviol or vita glass; the former are too sensitive to the shorter waves, the latter too insensitive. Either gives a practically useful means of studying the change of biological activity of any one type of source with age or running conditions. Neither is fully satisfactory for comparing sources of different types (e.g. a carbon with a mercury arc), but such comparison is probably meaningless since the physiological responses to the lamps are different in kind and cannot be approximated by any system of control of dosage.

SELENIUM CELLS AND THEIR USE IN SOUND FILM REPRODUCTION. By Dr H. Thirring.

The disadvantages of the selenium cell are discussed, and reasons are given why these do not interfere with the use of the cell for sound film reproduction. It is claimed that the quality of sound reproduction by means of selenium cells is equivalent to, if not better than, that obtained with the best alkali photo-electric cells.

THE MANUFACTURE OF SELENIUM CELLS. By Major C. E. S. Phillips, O.B.E., F.INST.P.

The paper contains a brief description of several methods of making selenium cells, together with a comparison of their relative merits. The effect of oil in reducing "lag" is pointed out. Sublimation *in vacuo* is referred to and attention called to the desirability of avoiding the formation of selenious acid in all cases where the cells are made at atmospheric pressure; a method is suggested whereby this may be accomplished.

INFRA-RED SENSITIVE CELLS. By Dr Fritz Schröter and Dr Fritz Michelssen.

The paper describes the method of preparing selenium-tellurium cells and thallium sulphide cells which are sensitive to the infra-red region of the spectrum. Curves are given showing the variation of sensitiveness of the different types of cell with wave-length. The application of such cells to telegraphy and telephony by means of bundles of invisible rays is discussed.

THE "THALOFIDE" CELL. By Theodore W. Case.

This cell is light-active to infra-red radiation and has its maximum action at a wave-length of about 1μ. A detailed description of its preparation and characteristics is given. Drawings disclosing its construction and the curve of its spectral sensitivity, together with the transmission curves of infra-red and visible radiation through the atmosphere, are shown. An efficient infra-red filter is described and its transmission curve is given. The circuit employed in infra-red signalling is shown and a brief description of the apparatus and the method of using it is given.